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Potential Effects of Irrigation Practices on Crop Yields in Grand Valley

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An analysis has been undertaken to determine the economically optimal seasonal depth of irrigation water to apply under conditions of both limited and plentiful water supply. The objective was to determine if general guidelines having practical utility could be postulated for all water supply situations. An extensive range of literature pertaining to the relationship between crop yield and the amount of water applied has been reviewed and differences suggested by various authors have been resolved. In addition, 32 plots of corn and 10 plots of wheat were grown under different irrigation regimes in the Grand Valley of Colorado to supplement the results of other researchers and to provide further insight into the effects of stress at different stages of plant growth. The results of the field experiments on corn and wheat show that irrigation can be terminated sooner than is the common practice in Grand Valley, which will result in benefits to farmers in increased crop yields and to downstream water users because of reduced saline return flows reaching the Colorado River.

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FOREWORD

The Environmental Protection Agency was established to coordinate administration of the major Federal programs designed to protect the quality of our environment.

An important part of the Agency's effort involves the search for information about environmental problems, management techniques and new technologies through which optimum use of the Nation's land and water resources can be assured and the threat pollution poses to the welfare of the American people can be minimized.

EPA's Office of Research and Development conducts this search through a nationwide network of research facilities.

As one of these facilities, the Robert S. Kerr Environmental Research Laboratory is responsible for the management of programs to: (a) investigate the nature, transport, fate and management of pollutants in groundwater; (b) develop and demonstrate methods for treating wastewaters with soil and other natural systems; (c) develop and demonstrate pollution control technologies for irrigation return flows; (d) develop and demonstrate pollution control technologies for animal production wastes; (e) develop and demonstrate technologies to prevent, control or abate pollution from the petroleum refining and petrochemical industries; and (f) develop and demonstrate technologies to manage pollution resulting from combinations of industrial wastewaters or industrial/municipal wastewaters.

This report contributes to the knowledge essential if the EPA is to meet the requirements of environmental laws that it establish and enforce pollution control standards which are reasonable, cost effective and provide adequate protection for the American public.

William C. Galegar

William C. Galegar
Director
Robert S. Kerr Environmental
Research Laboratory

PREFACE

This report is the second in a series of two reports resulting from U.S. Environmental Protection Agency Grant No. S-800687, "Irrigation Practices, Return Flow Salinity and Crop Yields." This report focuses upon the impact of various irrigation practices in determining crop yields, with particular emphasis on corn and wheat. The first report, "Irrigation Practices and Return Flow Salinity in Grand Valley" focuses upon the prediction of subsurface irrigation return flow salinity. These reports have been used as input to another research project conducted in Grand Valley and largely funded by the U.S. Environmental Protection Agency under Grant No. S-802985, "Implementation of Agricultural Salinity Control Technology in Grand Valley."

Three reports have been produced under Grant No. S-802985. The first report, "Implementation of Agricultural Salinity Control Technology in Grand Valley," describes the design, construction and operation of a variety of salinity control technologies implemented on farmers' fields. The second report, "Evaluation of Irrigation Methods for Salinity Control in Grand Valley," is concerned with the evaluation of furrow, border, sprinkler and trickle irrigation as individual salinity control alternatives. The third report of this series, "'Best Management Practices' for Salinity Control in Grand Valley," develops the methodology for determining the cost-effectiveness of individual salinity control measures, as well as a complete package of salinity control measures that should be implemented in the Grand Valley.

ABSTRACT

An analysis has been undertaken to determine the economically optimal seasonal depth of irrigation water to apply under conditions of both limited and plentiful water supply. The objective was to determine if general guidelines having practical utility could be postulated for all water supply situations. An extensive range of literature pertaining to the relationship between crop yield and the amount of water applied has been reviewed and differences suggested by various authors have been resolved. In addition, 32 plots of corn and 10 plots of wheat were grown under different irrigation regimes in the Grand Valley of Colorado to supplement the results of other researchers and to provide further insight into the effects of stress at different stages of plant growth.

There is an economically optimal depth of seasonal irrigation water to apply which is not particularly sensitive to irrigation efficiency or to the price of the inputs or the returns. The methodology shows how the correct depth of application could theoretically be obtained with more precision, but the conclusion is drawn that such precision is unrealistic. The answer is given within the bounds of the accuracy of application for the given irrigation method. The results are extended to conditions where irrigation provides only a supplementary portion of the crop water supply, and to include a range of crops within the enterprise. In addition, management practices which allow the most effective use of the available water supply are discussed.

The results of the field experiments on corn and wheat show that irrigation can be terminated sooner than is the common practice in Grand Valley, which will result in benefits to farmers in increased crop yields and to downstream water users because of reduced saline return flows reaching the Colorado River.

This report was submitted in fulfillment of Grant No. S-800687 by Colorado State University under the sponsorship of the U.S. Environmental Protection Agency. This report covers the period of February 18, 1974 to June 17, 1977, and was completed as of August 31, 1978.

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SECTION 1

INTRODUCTION

BACKGROUND

From the time that man first developed the art of artificially applying water to the land he has been faced with the problem of how to best allocate the available water supply to his crops. Before the advent of river regulation his alternatives were limited, as in many areas he had to take the water in the spring when it was available, spread it over the area he could command and hope that the flow would be sustained sufficiently long to bring the crop to the stage of harvest.

But what of that low flow late in the season? Should it be spread to all of the land area being cropped, or should it be restricted to a smaller area from which maximum yields could be obtained? Even with the advent of river regulation, in which the flow can be adjusted to meet the fluctuating demands of the crops, should an attempt be made to irrigate as much land as possible with the water allocated to irrigation, or should peak yield be striven for on a smaller land area?

In some areas, the question has been answered (but not solved) by allocating a water supply which is sufficient to fully satisfy the crop needs of the given irrigated area. Often, in fact, the allocation is greatly in excess of the requirements of the crops (i.e., Grand Valley). Even in this case, though, the application of water will have an associated cost for water delivery, as well as environmental detriments, and the question of the optimal depth of water application will still exist.

The question takes on perhaps greater significance in situations where the quantity of water available for irrigation is less than adequate to supply the potential crop requirements over the available land area. This is a fairly common case and may be due to a variety of causes in addition to inadequate or unregulated river flows. For example, the availability of groundwater has induced many farmers to irrigate until the point has been reached in many regions where the water is being withdrawn at a rate faster than it is being replenished. The realization that the groundwater supply is finite, coupled with the high cost of pumping from an aquifer with a declining phreatic level, has caused an economic, and in some areas, legal limit to be placed on the quantity able to be withdrawn. In many areas of the world, legal volumetric limits are also extended to surface water supplies.

Similarly, farmers irrigating from on-farm reservoirs, in which intermittent runoff is captured, usually have available to them a supply less than adequate to provide full crop water requirements over the irrigable land area. Irrigation based on the uncertainty of supply often associated with on-farm water conservation must make the best possible use of the available resource. Any water carryover from one season to the next reduces the risk of failure in the ensuing season.

Some irrigation districts operate a water market in which farmers may rent or lease their excess water to those requiring additional supplies. If the irrigator has the opportunity to rent or lease the excess water he must decide to what level his irrigation should be restricted. A farmer could conceivably increase his economic return by properly managing a smaller volume of water and disposing of the excess so saved.

In recent years there has been a growing concern with water quality degradation resulting from irrigated agriculture. The solutions to this problem have been identified as improved water management practices. However, improving the present practices of allocating and using water to achieve high levels of irrigation water management requires a fundamental knowledge of crop yield-water use functions.

In addition to the physical and economic reasons outlined above, social and political factors may also intrude to cause the available water supply to be spread over a larger area than that which would allow total satisfaction of crop needs. These may not necessarily include the host of other environmental, social and economic causes which compete for the water that was once reserved almost exclusively for agriculture.

Those irrigation planners who have considered the problem of optimal depth of irrigation application are divided on the answer. Many would appear to agree with Stewart, et al. (1973) who state in the case where water is limited in relation to the available land area, that:

> the optimal seasonal (irrigation) depth for profit maximization will be one unit (or as few units as practicable) greater than (irrigation) at the economic break-even point.

On the other hand, Hillel (1972) feels that:

> Traditionally, the great fallacy in water management has been the tendency to save water per unit of land area, in order to "green up" more land. Some of the agricultural planners in Israel, as well as in other arid countries, have fallen prey to this fallacy. We must remember that our basic aim is not to save water but to increase production efficiency by optimizing the water supply (and other environmental variables) so as to maximize plant response. The best chance of increasing production efficiency by water management is to obviate water stress and prevent water from becoming a limiting factor in plant growth.

PROJECT OBJECTIVES

A total of eight objectives were outlined for this research project. They are as follows:

1. Evaluate the effects of various irrigation practices on the amount and chemical quality of return flows.
2. Evaluate the effects of various irrigation practices on crop yields and fertilizer requirements.
3. Demonstrate that improved farm management of irrigation water can reduce the mineral content of return flows.
4. Demonstrate that improving the chemical quality of irrigation return flows through better farm irrigation practices is profitable due to increased crop yields and reduced fertilizer expense.
5. Provide a better understanding of the manner in which water quality degradation takes place as a result of irrigation.
6. Develop recommendations regarding irrigation systems, methods, and practices which will minimize the chemical quality of return flows while maintaining a good crop environment and maximum benefits from the consumed water.
7. Develop procedures for projecting the findings of this study to basinwide evaluations.
8. Provide useful information for future salinity studies concerned with farm management.

An accompanying report, "Irrigation Practices and Return Flow Salinity in Grand Valley" addresses the objectives 1, 3, 5, 7 and 8. This particular report addresses objectives 2, 4 and 6, with particular emphasis upon the relations between irrigation practices and crop yields, and only limited emphasis on fertility. Objective 6 is also covered extensively in a companion project report, "Evaluation of Irrigation Methods for Salinity Control in Grand Valley." All of these reports have been delineated to serve the needs for the final report in this series, "'Best Management Practices' for Salinity Control in Grand Valley."

The objectives of this study were expanded to determine the correct seasonal depth of irrigation water to apply under any water supply situation. In the case where the water supply is limited relative to the available land area, the determination of the optimal depth of application will determine the area able to be commanded by the water supply. In the case where water is plentiful relative to the available land area, the determination of the optimal depth of application will determine the quantity of water that must be supplied. The objective is to develop an answer that has universal rather than site-specific application and to show the impact of irrigation methods and management practices on the interrelationship between the water supply, land area and profits.

APPROACH TO STUDY

The optimal allocation of irrigation water will obviously depend on the relationship between yield and the crop's water supply. Data on this relationship have been collected since the late 19th century and some of the most comprehensive and revealing studies are reviewed in Section 4. Only in recent years have the equipment and techniques become available to enable yield to be related to evapotranspiration under field conditions. An endeavor has been made to review the available literature on this subject.

As the body of knowledge is not large and as there is difficulty in drawing common conclusions from the published reports, an experiment was undertaken with hybrid corn (Zea mays L.) and winter wheat in order to partially fill the informational gap and to provide firsthand insights into the reaction of crops to stress at different stages of growth. This experiment was carried out near Grand Junction in the Grand Valley of western Colorado.

Using the Grand Valley results in conjunction with the results of other researchers, a method has been developed to determine the economically optimal seasonal depth of water application under conditions of both limited and plentiful water supply. Every effort has been made to arrive at a general result having universal application, rather than to develop a complex computational procedure of limited and specific application. A basic hypothesis has been that if the depth of application can be obtained with an accuracy which is within the limits of accuracy of application of the given irrigation method, then this will be of far greater value than a complex computer model that may obtain the answer with a little more precision, but which may, in fact, be spurned in practice because of its complexity (although this is not to deny the value of such models in the appropriate solution). In addition, the results obtained by such a model would only be as good as the parameters and constraints upon which it is based, which, in an agricultural situation, are often difficult to model any better than idealistically. The objective has been to see if a correct answer exists that only depends on the relative magnitude of the parameters rather than on absolute magnitudes.

As the optimal allocation of irrigation water depends on the relationship between yield and water applied, factors affecting the form of that relationship obviously will affect the calculations of the optimal depth of allocation. Factors which will influence the relationship include the degree of dependence of the crop on irrigation, the management practices under which the crop is grown, and the inherent limitations of the irrigation system used to water the crop. Viewed from the opposite perspective, an examination of the factors affecting the crop yield-water use functions will allow an evaluation of those factors in terms of their impact on farmer profitability, return flow salinity, and downstream detriments.

SECTION 2

CONCLUSIONS

This field study has capitalized on recent research results of other investigators to substantiate the functional relationship between water use and crop yields. This research has focused upon the implications of this relationship in reducing the salt load from the Grand Valley that is presently reaching the Colorado River. Many of these conclusions are applicable to all irrigated areas.

1. In this study, the crops were subjected to different irrigation regimes and the yields of mature dry matter forage, and grain, as affected by the different regimes, were compared. The timing of moisture deficits has a significant effect on dry matter yields as well as on grain yields. The result appears reasonable when it is considered that the grain component of many crops makes up a substantial portion of the dry matter yield.

2. The corn crop was differentiated into three growth stages after establishment, designated successively the vegetative, pollination and grain-filling periods. Stress was applied in one or more of these periods by eliminating irrigation. The crop was harvested for both grain and dry matter.

    a. A notable effect was the severe depression of yield caused by stress during the pollination period. Any evapotranspiration (ET) deficits occurring in this period alone would appear to restrict the upper limit of both grain and dry matter yields, irrespective of subsequent irrigations.

    b. If deficits have also occurred in the vegetative period, the crop may be somewhat conditioned to stress and the detrimental effect of the pollination period stress may be lessened in terms of water use efficiency. In this case, a late irrigation is likely to elicit a small positive response.

    c. Where the crop has been well watered through the first two growth stages, irrigation during the grain filling period may be of no benefit to yields and may even be detrimental, particularly to grain yields.

    d. Maximum efficiency, in terms of grain yield per unit of water used by the crop, occurred when irrigated through the vegetative and pollination stages of development.

    e. Forage yield results showed that the vegetative stage was the more critical period with respect to water deficits and dry matter production. The highest return on water use was 279 kg per cm, occurring when the crop was irrigated only through the vegetative stage of development.

    f. Maximum yields of forage corn was obtained by those treatments where the corn was irrigated during the vegetative and later growth stages. A substantial saving in water can be achieved by the elimination of irrigation during the maturation stage of development (grain filling) and at the same time, maintain yields of grain and forage at a high level.

    g. An important result which is not unique to this study is that the maximum ET of a crop does not necessarily correspond to the maximum yield. This was found for corn and wheat.

3. The wheat grown in this experiment was subjected to different irrigation treatments only in the latter stages of its development (from the late boot stage onwards) and was harvested only for grain. The crop was differentiated into two subsequent growth stages--the anthesis period and the grain filling period.

    a. Little response to irrigation in the grain filling period occurred, irrespective of earlier irrigations.

    b. Irrigation during the anthesis period was of considerable benefit, although stress during the earlier shooting stage may even have limited the effectiveness of this irrigation.

4. To determine the economically optimal allocation of irrigation water to a given crop, the relationship between the yield of the crop and its use of the supplied water must be known. Studies of this relationship, particularly those considering the yield of the reproductive organ of the crop, have generally resulted in a curvilinear line of best fit being drawn through a scatter of data.

5. More recent studies, including that undertaken herein, indicate that this scatter of data largely results from the time of occurrence of water deficits in relation to the stage of growth.

   a. Crops are far more sensitive to moisture stress during some stages (i.e., pollination in corn) than others.

   b. If a crop is supplied a seasonal quantity of water less than its potential requirements, exaggerated yield reduction could occur if the deficit occurs during periods of such sensitivity.

   c. The scatter in data can be considerably reduced, therefore, if deficits are so timed that they cause the least yield reduction for the given quantity of water supplied.

6. If crop yields are plotted against evapotranspiration (ET) rather than the quantity of water supplied, the data will fall on a straight line, this line representing the upper bound of yield for a given quantity of ET.

   a. When the upper bound on yield is plotted against the water supply available to the crop, a concave downwards function results.

   b. The horizontal difference between the linear function and the curvilinear function is the amount of water supplied but not used in the evapotranspiration process, i.e., losses.

   c. High water application efficiencies will be associated with small losses, resulting in a yield versus supplied water function which will be close to linear.

7. All of the conclusions drawn from this study are based on functions representing the upper bound of the yield-water use relationship, i.e., those representing irrigation regimes in which any deficits are sequenced to occur at the least damaging times.

    a. This premise is reasonable in that it represents the ultimate goal of the irrigation farmer.

    b. The linear yield-water use (ET) function may be thought of as the ideal, with curvilinear relations diverging from the linear function representing deviations from the ideal.

    c. The relative proximity of the field production function to the ideal allows an evaluation of irrigation management practices and irrigation system performance.

8. On heavy soils, such as encountered in Grand Valley, irrigation can be halted before the crop has reached physiological maturity, allowing the stored soil moisture to carry the crop through to harvest, which will:

    a. Improve crop yields.

    b. Allow the soil to be drier for harvest.

    c. Allow better utilization of interseasonal precipitation.

    d. Retain more nutrients in the root zone, particularly nitrogen, for use by subsequent crops.

9. Although very efficient irrigation practices were used in this research, the results based on vacuum extractor data clearly showed that most of the losses of nitrate fertilizer by deep percolation occurred early in the irrigation season. These fertilizer losses would have been more dramatic if the usual irrigation practices employed by farmers in Grand Valley had been used.

10. The relationship between crop yields and water use has formed the basis of the analysis to determine the economically optimal seasonal depth of irrigation water to apply. Both the analyses used and the results obtained will differ depending on whether water is relatively scarce or relatively plentiful.

11. In the case where the quantity of water for irrigation is limited relative to the available land area, the correct seasonal depth of water to provide is that which will satisfy the ET requirements of the crop, plus a small margin for leaching salts from the root zone, rather than spreading the limited water supply over too much land.

    a. For systems with very high application efficiencies, such as 90 percent for trickle irrigation, the correct depth of water application may be obtained by dividing the ET corresponding to the method of irrigation by the efficiency.

    b. For systems with low efficiencies, the problem becomes more complex. An important consideration is whether a change in the method of water application would be appropriate, particularly when the large quantity of irrigation return flows resulting from an inefficient system results in significant water quality degradation.

12. In the case where the quantity of water available is plentiful relative to the land area, the correct irrigation policy is to apply a seasonal depth of irrigation water which will allow close to maximum yields to be attained. The shape of the yield production function, which is dependent on the irrigation efficiency, will determine "how close."

    a. For highly efficient irrigation, the production function will be only slightly nonlinear and the objective should be to irrigate to achieve maximum yields.

    b. For less efficient irrigation, the correct depth of application for the farmer will depend on the price ratio (ratio of marginal cost of water to marginal net income), while the application depth will be considerably less in those cases where the irrigation return flows cause water quality degradation.

13. The water allocation model ultimately depends on the mathematical relationship between crop yield and water use. Therein lies its inherent weakness.

    a. To use yield versus water supply (or water applied) functions destroys any uniqueness, and hence predictive capability, of the relationship.

    b. The unique yield versus ET relationship can be used, but the efficiency of application for each area to which it is applied must be known in order to determine the optimal allocation.

SECTION 3

RECOMMENDATIONS

The conclusions resulting from this particular research effort have led to the following recommendations that should be incorporated into an "action" salinity control program for Grand Valley.

1. An awareness program should be undertaken to acquaint irrigators with the advantages of terminating the irrigation of corn and grain crops earlier than is presently practiced in the Grand Valley. There are benefits in both reduced salinity and increased crop yields.

2. Improved agronomic practices should be given as much consideration as the construction of physical improvements when implementing a full-scale salinity control program in Grand Valley. Farmers will be more receptive to adopting improved agronomic practices at the same time that physical improvements are constructed. Improved agronomic practices can provide substantial benefits to farmers, thereby facilitating also the adoption of improved irrigation methods and practices, which in turn will provide substantial benefits to downstream water users because of reduced salinity concentrations.

3. Improved agronomic practices should be incorporated into the irrigation scheduling service to be provided under the action salinity control program for Grand Valley. An effective irrigation scheduling service should use improved irrigation practices based upon an evaluation of each field in the Valley.

4. Existing agronomic research from other locations in the West should be reviewed in order to develop irrigation guidelines for each of the major crops that take into account the requirements for irrigation return flow quality control.

5. The economic advantages to farmers in adopting more advanced irrigation methods, such as sprinkler or trickle, should be documented in a style that is meaningful to farmers. These irrigation methods have definite advantages for reducing the salt loads reaching the Colorado River, as well as increasing crop yields. Salt loads will be reduced because of significant reductions in deep percolation losses early in the season and a smaller reduction late in the season as a result of earlier termination of irrigation. Crop yields will be increased as the result of increased fertilizer use efficiency, a more favorable root-zone environment for crop growth and earlier termination of irrigation. These interrelations are becoming increasingly important for farmers to understand.

SECTION 4

CROP RESPONSE TO IRRIGATION REGIME

CROP YIELD-WATER USE FUNCTION

Crop yield-water use functions form the basis for decisions regarding the allocation of irrigation water. An explanation of the importance and uses of production functions has been given by Minhas et al. (1974):

> To study the question of economically optimal use of water, we need to know the exact shape of the crop response function to different quantities of water used by the crop throughout its growth cycle. For instance, consider a large reservoir system. The problems of scheduling the operations of the system include decisions on the timing of water releases and the allocation of water among crops. The allocation decisions are relevant also for the operation of tube wells or run-of-the-river irrigation systems. Unless we have the knowledge of the marginal productivity of water allocated to each crop at different stages of its growth, we cannot arrive at an optimal set of decisions. This knowledge is required also in determining the extent of the command area of an irrigation system. A production function for each crop, in which yield is related to dated inputs of water, will provide such knowledge.

Crop production functions in this study are considered particularly within the framework of on-farm allocation of a limited supply of irrigation water; however, this allocation is the starting point in deciding the allocation of water within the overall system, to which the results are equally applicable. Decisions on allocations may be among projects, as well as among crops, soil types and locations within projects. The decision could be between agriculture versus other uses. The production functions will affect the design of water conveyance, distribution and irrigation systems, since they should determine the scheduling of water releases and consequent irrigations. Production functions also allow the economic impact of water shortages in irrigated agriculture to be assessed.

Some of the earliest production functions were obtained by researchers investigating the effects of precipitation and soil moisture on dryland crop yields. Cole (1938) studied the relationship between annual precipitation and the yields of spring wheat on the Great Plains. Taking 272 data points from 14 research stations in the northern Great Plains over the period 1906-1935, he obtained the linear regression equation:

$$\text{yield} = (\text{precipitation}-8.02)2.19 \;.\;.\;.\;.\;.\;.\;.\;. \quad (1)$$

with a correlation coefficient of 0.74, where the yield was measured in bushels per acre and the precipitation in inches for the year ended 31st July. Cole recognized that it may have been more satisfactory to use the precipitation from the actual date of one harvest to the next, in order to more nearly represent that moisture available to the crop, but this would introduce data not so readily available or readily determined. Using 31st July as the year end placed the data close to harvest and allowed uniformity of data. When the yield and precipitation of the 14 stations were averaged for each of the 30 years, Cole obtained from the 30 data pairs the regression equation:

$$\text{yield} = \text{precipitation}-10.07)3.19 \;.\;.\;.\;.\;.\;.\;.\;. \quad (2)$$

with a correlation coefficient of 0.88.

Leggett (1959) related the yield of wheat in eastern Washington dryland areas to available moisture and nitrogen for the years 1953-1957. He obtained the regression equation:

$$\text{yield} = 5.8(SM + R) - 23.8 \;.\;.\;.\;.\;.\;.\;.\;.\;.\;.\;. \quad (3)$$

with a correlation coefficient of 0.87, where SM is the available soil moisture in the spring and R is the rain which fell during the growing season. A higher correlation coefficient (0.91) between yield and total moisture was obtained for the experiments conducted under annual cropping and a lower correlation coefficient (0.77) for those conducted on fallowed ground. Curvilinear regression analysis of the data did not improve the relationship between yield and total available moisture and therefore Leggett assumed the relationship was linear over the range of moisture and yield considered.

Attempts to develop production functions for irrigated crops have been numerous, for the reasons mentioned at the beginning of this section. Comparison of the production functions obtained by different researchers is difficult as different coordinates are often used. The ordinate is generally expressed as yield. In some cases relative yield is used, where the yield is expressed as a percentage of the maximum yield obtained at that location. The latter method may allow some degree of transferability of production functions, with the relative yield at one location multiplied by the maximum yield at another thereby giving (theoretically) the absolute yield at the second location for the given quantity of water. Many terms have been used for the abscissa, ranging from transpiration to the amount of water applied. For comparitive and useful purposes, a common and reproducible term is obviously required. Evapotranspiration would appear the most suitable as it is usually computed or measured, although it may be dependent on the method of water application. Using transpiration would overcome this objective, but measurement under field conditions is difficult. Using the amount of water applied as the abscissa makes comparison of crop production functions difficult, as they will then vary with the method of irrigation and the practices adopted.

Different shapes of the function relating yield to water use have been obtained by different researchers. The strongly linear relationship between wheat grain yield and precipitation, obtained by Cole (1938) and Leggett (1959), has been supported by container and field experiments which have demonstrated for many crops a linear relationship between yield and water use until maximum yield is obtained. Perhaps more numerous, however, are the field experiments showing that the relationship between yield and applied water is concave downwards. In this instance, the curve rises monotonically to a maximum value of yield and then in some cases flattens to a plateau, while in other cases the curve shows a decrease in yield with increasing water use.

Some of the more illustrative experiments and studies in which crop yield-water use functions were obtained are reviewed to show alternative forms of the function and to allow an examination of the parameters involved. This includes both linear and nonlinear functions. The review forms the basis for the resolution of the form of the relationship, which is presented in a subsection below.

Until the development of the neutron meter for rapid, nondisturbing soil moisture measurement, accurate measurements of crop evapotranspiration were practically limited to experiments carried out in containers. This is still largely true for crop transpiration measurements. One of the most comprehensive studies of the dry matter yield-transpiration relationship was undertaken by de Wit (1958), who studied a wide range of data collected for common field crops grown in containers from which evaporation was controlled or measured. The results of many of the observations are presented in Figure 1. In the cases where the relationship varied from linear, de Wit considered this to be associated with poor aeration of the root system.

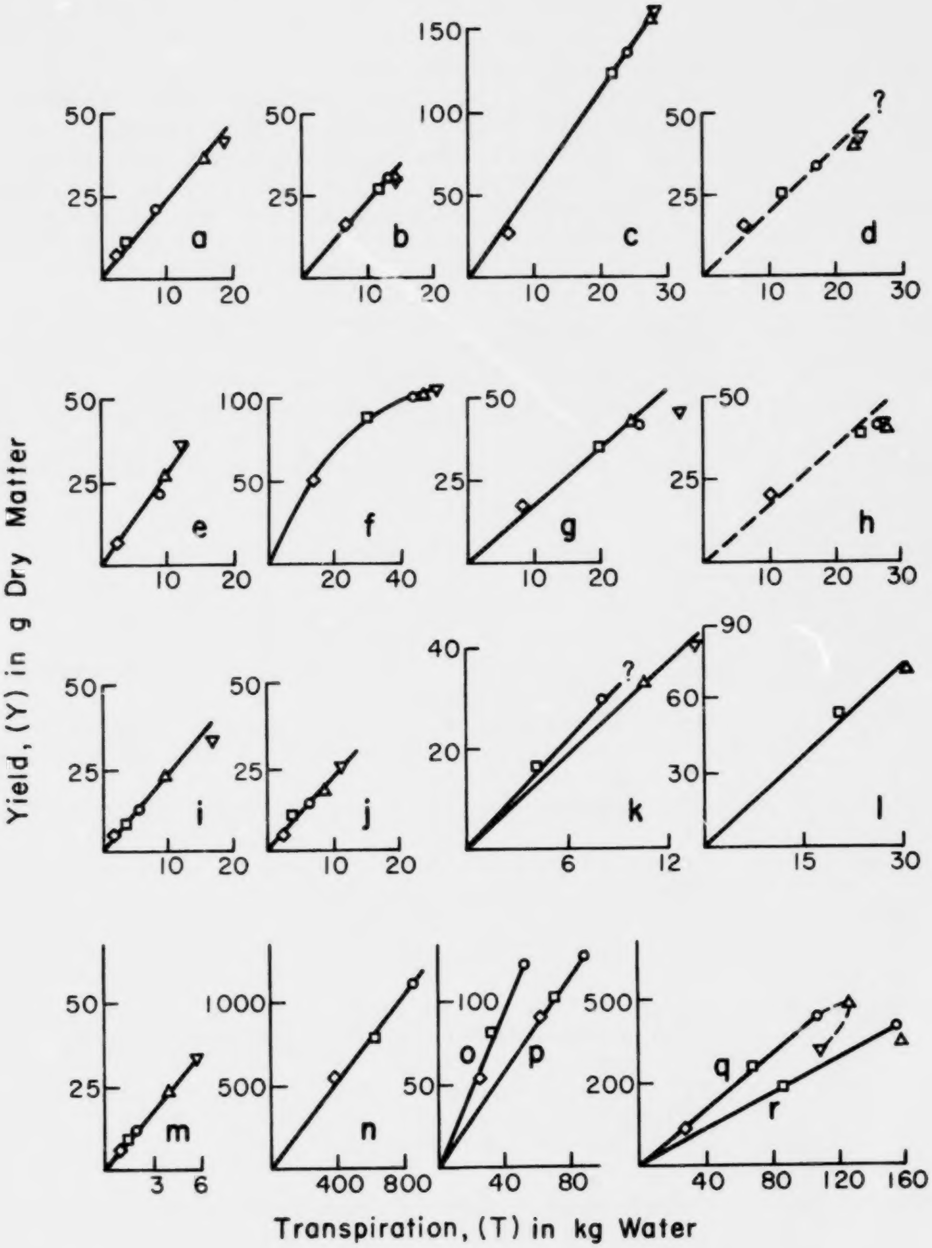


Figure 1. Yield versus transpiration of plants grown in containers with soil at different moisture contents (from de Wit, 1958).

Explanation of Data Sources. (Details in original publications, referenced in de Wit, 1958).

graphs a-j:	Data from Schultz (1927). Availability of water between (∇) 76-95%, (Δ) 57-95%, (○) 38-95%, (□) 19-95%, (◇) 0-95% of the water holding capacity of the container. a: serradella; b: mustard; c: sorghum; d: hairy vetch; e: carrots; f: oats; g: meadow foxtail; h: meadow fescue; i: red clover; j: white clover.
graph k:	Crop: peas. Data from Boonstra (1934). Availability of water (∇) 90, (Δ) 70, (○) 50, (□) 30% of water holding capacity. Average two varieties harvested around July 10, 1930.
graph l:	Crop: oats. Data from Van der Paauw (1949). (Δ) wet and (□) dry series.
graph m:	Crop: corn. Data from Haynes (1948). (◇) initially water only (plant died); (□) small portion of roots sparingly irrigated (plant died); (○) irrigated field capacity at permanent wilting perc.; (Δ) irrigated to permanent wilting perc. to field capacity at 20 inches Hg pressure at; (∇) water table 6 inches below soil surface.
graph n:	Crop: alfalfa. Data from Scofield (1945). (◇) infrequently irrigated; (□) frequently irrigated; (○) sub irrigated.
graphs o, p:	Crop: oats. Data from Dillman (1931). (◇) severe wilting during heading and milking stage; (□) severe wilting during heading stage; (○) regular supply of water. o: Newell; p: Mandan.
graphs q, r:	Crop: corn. Data from Kiesselbach (1916). q: 1910. (◇) 35, (□) 45, (○) 60, (∇) 80 and (Δ) 100% of the water holding capacity. r: 1913. (□) 50, (○) 70 and (Δ) 95% of the water holding capacity.

Figure 1 (continued).

To allow transferring or comparing results from different areas, he proposed the relationship:

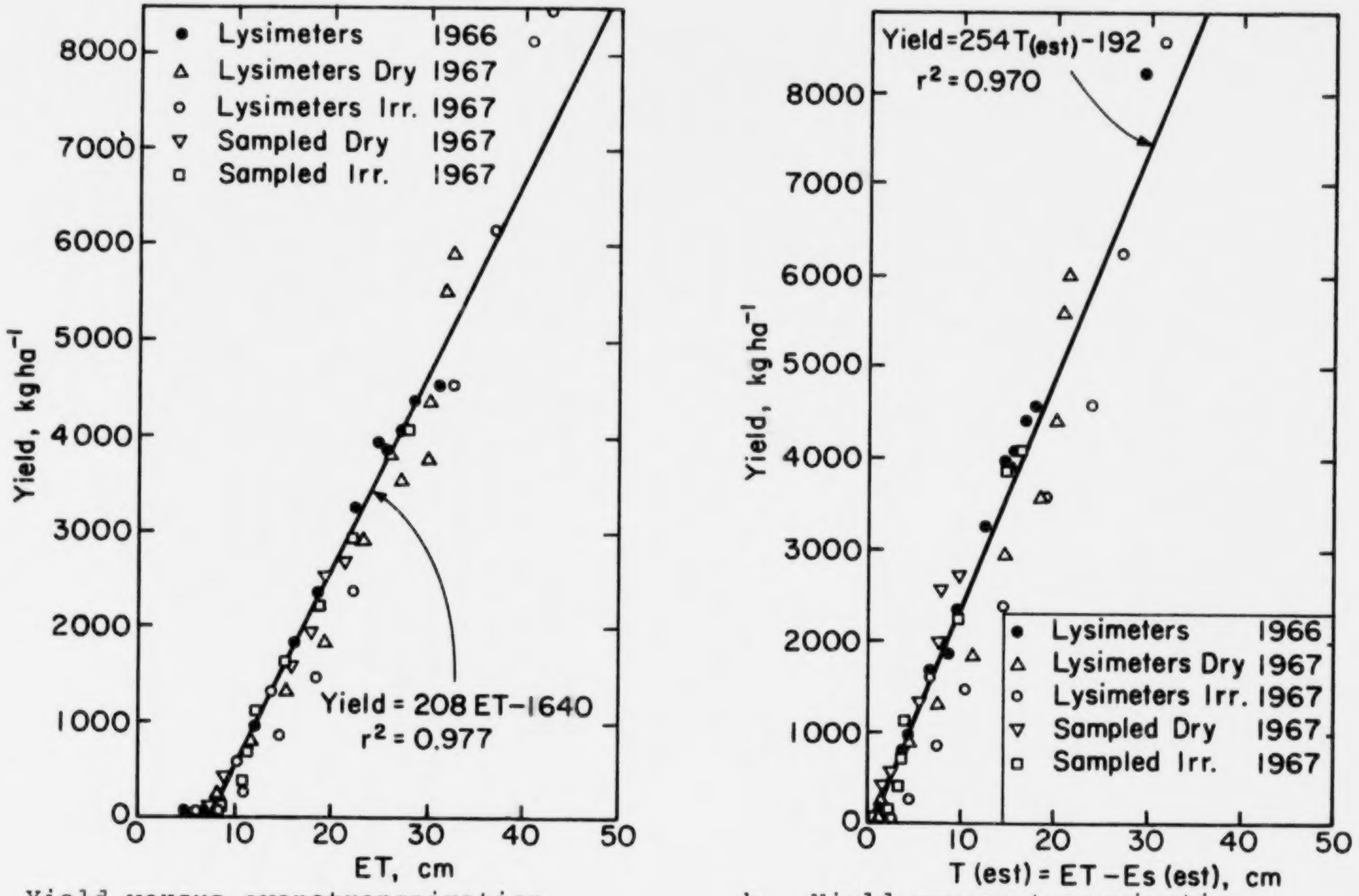
$$y_{DM} = mTE_o^{-n} \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (4)$$

where y_{DM} = total dry matter yield
T = total transpiration during growth
E_o = free water evaporation

The coefficient m varied for different crops, while the exponent n was found to be about 1 for the Great Plains of the USA and about 0 in the Netherlands. Although data were unavailable, de Wit hypothesized that there probably are regions where the value of n is somewhere between 0 and 1.

Arkley (1963) developed a method of comparing directly yield-transpiration functions obtained at diverse sites. In doing so, he took data from many experiments in the literature where plants were grown in containers with evaporation from the soil prevented, for example, by sealing all openings in the containers with wax. Arkley plotted the yield of dry matter versus transpiration corrected for mean relative atmospheric humidity during the period of most active growth (H) whereas de Wit had used a correction based on free water evaporation. Graphs of dry matter yield versus T/(100-H) were plotted for a wide range of crops from sites around the world; the crops included barley, oats, wheat, corn, millet, alfalfa, carrots snapdragons and weeds. All the graphs showed a linear relationship with a very high correlation coefficient. In most cases, the line of best fit also passed through the origin, showing that yield of dry matter was directly proportional to the transpiration. Arkley concluded that deviation from a straight line with increasing moisture revealed the effect of overirrigation, while reversal in the slope of the line suggested waterlogging or poor aeration in the soil.

Hanks et al. (1969) plotted the cumulative dry matter yields of wheat, oats, millet and grain sorghum obtained at the United States Department of Agriculture (USDA) Central Plains Field Station at Akron, Colorado, against evapotranspiration. In all cases, a strong linear relation existed. For sorghum, an estimate of evaporation from the soil (E_s) was made and subtracted from evapotranspiration to allow an estimate of transpiration. The data showed a high linear correlation of yield with transpiration (coefficient of determination of 0.97), with the line of best fit passing through the origin. Hanks et al. (1969) consider this to be a strong evidence that for grain sorghum, dry matter production is directly proportional to transpiration. The yield versus evapotranspiration and yield versus transpiration relations are shown in Figure 2.



a. Yield versus evapotranspiration b. Yield versus transpiration

Figure 2. Relation of cumulative dry matter yield of grain sorghum to evapotranspiration and transpiration (from Hanks, et al., 1969).

A linear relationship between dry matter yield and evapotranspiration was also obtained by Hillel and Guron (1973) in a well-monitored 5-year experiment with corn in Israel. The relationship between grain yield and evapotranspiration was also found to be linear. Both relationships are shown in Figure 3.

A recent and comprehensive endeavor to develop methods for predicting crop yields has been made by the Consortium for International Development (1976) experimenting with corn at Davis, California; Yuma, Arizona; Logan, Utah and Fort Collins, Colorado. One of the objectives was to develop production functions which reflect influences on yields of different water supply levels and moisture tensions within the root zone at different stages of crop growth. This was achieved by the experimental design in which all irrigation after the establishment of the crop was from a single sprinkler line parallel to the rows through the center of the plots. The closely spaced sprinkler heads threw a triangular water pattern such that maximum water application occurred at the sprinkler line, tapering evenly away with distance (see Figure 4.) The growing season was divided into three time periods (growth stages) after establishment of the crop, these periods being the vegetative period, the pollination period and the maturation period. Control plots received water during all three growth stages. This treatment was designated III, with each I representing irrigation in the corresponding growth stage. Other plots had irrigation halted for the duration of one or more growth stages. The absence of irrigation during a particular stage was designated by the symbol 0. For example, where the crop received water in the vegetative and maturation period, but not in the pollination period, the treatment was designated I0I. This arrangement allowed severe deficits to be imposed during different stages of growth. In addition, different degrees of stress were imposed within a given treatment, with those plants furthest from the sprinkler line being most severely stressed.

For the control treatment, and generally within any given treatment, the relationship between yield and ET, in most cases, was strongly linear, for both dry matter and grain production. The upper bound on all of the data was also linear. As an example, a plot of the data relating yield to ET at Fort Collins is shown in Figure 5. Here, the yield associated with the highest values of ET can be seen to decline from those of the same treatment with a lower ET, which if Arkley's (1963) suggestion is followed, indicates poor aeration in the root zone.

The extrapolation of the upper bound line intercepts the abscissa to the right of the origin. This is in contrast to the correlation with transpiration, discussed above, in which the line passes through the origin. Hanks et al. (1969) also extrapolated the linear regression line down to zero yield

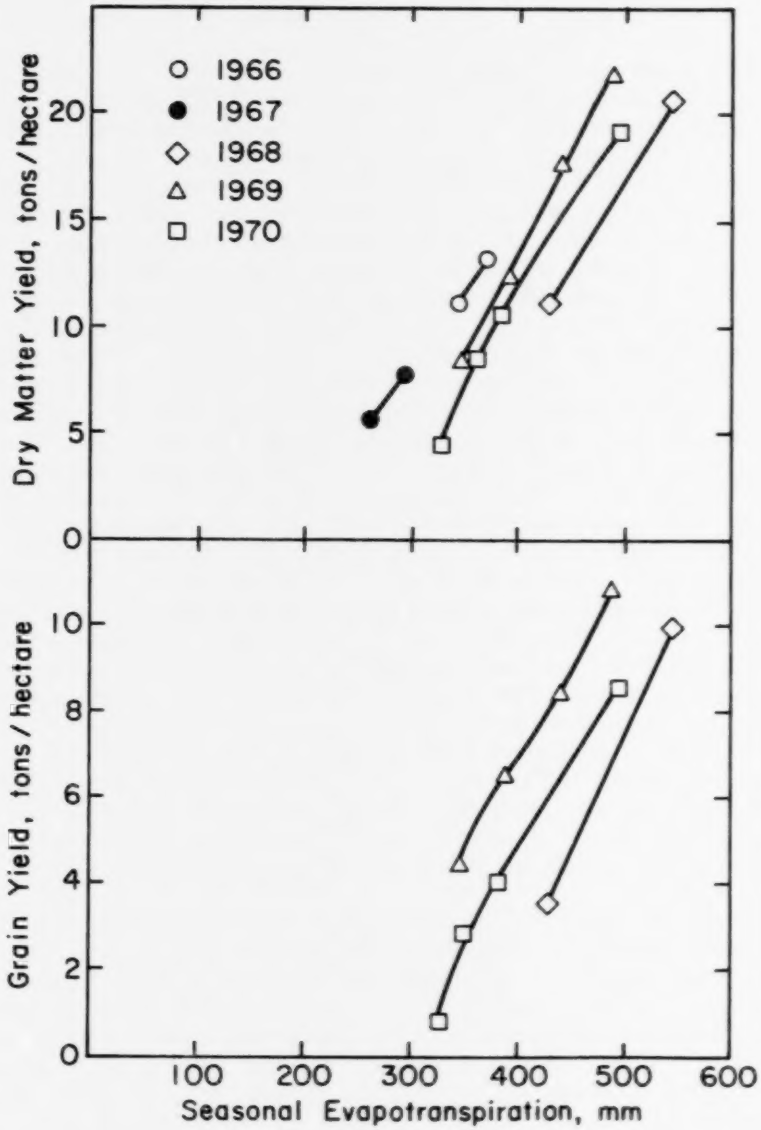


Figure 3. Relation of dry matter and grain yield of corn to seasonal evapotranspiration (from Hillel and Guron, 1973).

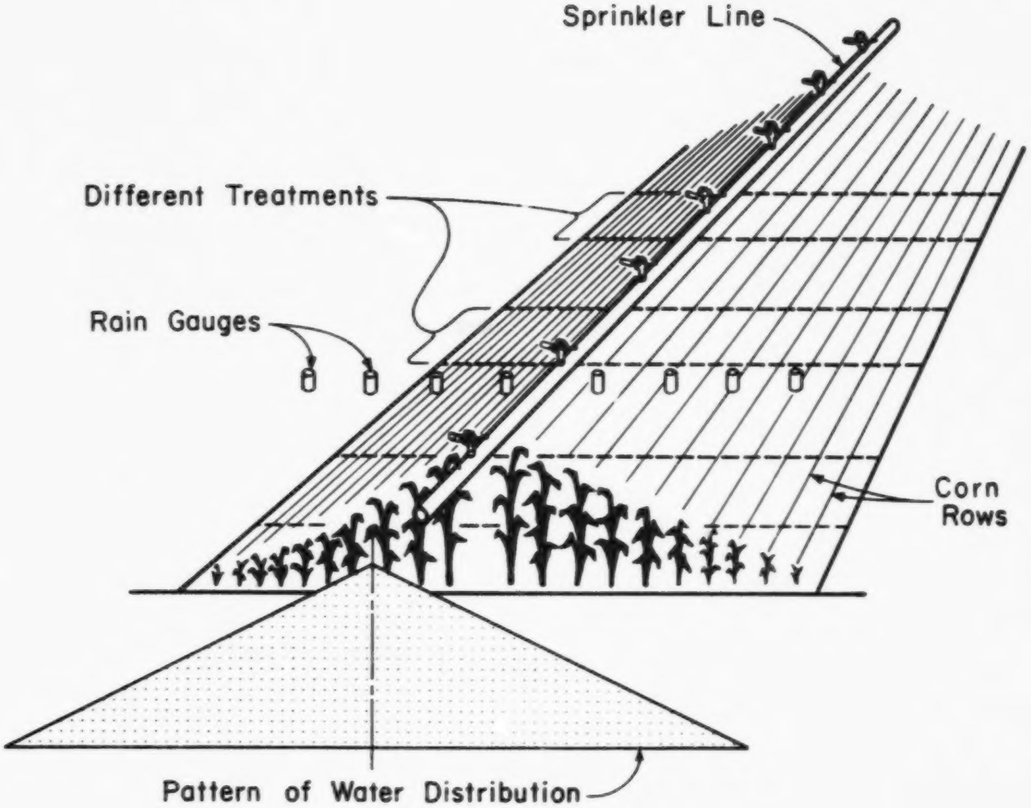

Sprinkler Line
Different Treatments
Rain Gauges
Corn Rows
Pattern of Water Distribution

Figure 4. Schematic of the experimental layout adopted by the Consortium for International Development.

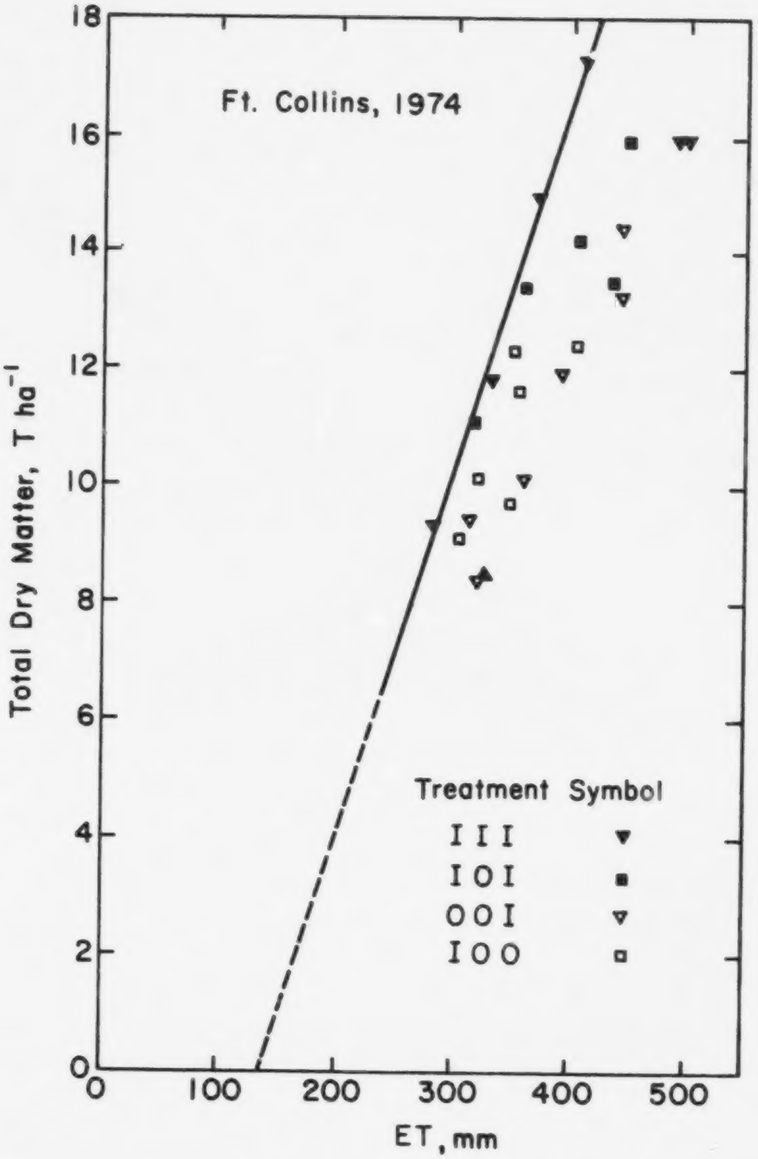


Figure 5. Corn dry matter yields from several irrigation timing treatments, related to seasonal evapotranspiration depths, Fort Collins, 1974 (from Consortium for International Development, 1976).

to find for four experimental crops a positive value of ET required before any yield was obtained. Evidently, with non-forage crops, a considerable proportion of the water used is required to bring the crop to the stage of reproduction. Unless this basic amount of water is available, no yield will result (Downey, 1972). Leggett (1959) found, for example, that approximately 100 mm of water are required to bring wheat to the heading stage under dryland conditions in eastern Washington. There appears to be a distinct intercept or threshold value of evapotranspiration below which production of grain is negligible. The threshold evapotranspiration value may be due largely to the water loss caused by direct evaporation from the soil surface as well as perhaps to the occurrence of some transpiration in late season from the senescing plants after cessation of growth. It is still possible, therefore, that production is proportional to net transpiration during the main growing season (Hillel and Guron, 1973).

One of the most comprehensive studies of crop yield-water use relationships has been compiled by Shalhevet et al. (1976) for a wide range of crops grown at a number of locations in Israel over the period 1954-1971. Production functions are presented in graphic and algebraic forms in terms of relative yield and net or gross water application. The authors used relative yield rather than absolute yield as a simple way of presenting data from different locations and years in a uniform manner. Net water application was the actual amount of water added to the soil following an irrigation, rather than the amount actually delivered. The authors used this parameter to reduce variability due to application efficiency and soil conditions. In all the experiments reported, irrigation efficiency was 80-90 percent, and the authors felt that by correcting for efficiency, the data obtained may also be applied to conditions other than those of the experiments. A linear regression was applied to the data of most field crops in the range from zero to 95 percent relative yield. Good fits were obtained for wheat, sorghum, grain and forage corn, cotton and tomatoes, with coefficients of determination ranging from 0.70 to 0.97. Curvilinear functions were fitted to the results of sugar beets, where the abscissa was net water application in the spring, and to alfalfa, where the abscissa was gross water application. Regression analysis gave indeterminate results for orchard crops.

As mentioned earlier, results showing a nonlinear relationship between yield and water use are probably more numerous than linear relationships. For example, in an experiment in which grain sorghum was grown in lysimeters, Howell and Hiler (1975) found only a weak correlation between yield and seasonal ET (linear correlation coefficient equal to 0.64). In experiments conducted by Evans et al. (1960) in the Willamette

Valley of Oregon, where yield of unhusked cobs of sweet corn was plotted against consumptive use under four different moisture treatments, the four points so obtained fall on a concave downward curve in both years of the experiment. These results would appear incompatible with the results reviewed up to this point, except that the effect of the timing of the water deficits has not been included. The importance of the timing of deficits, including the effect on the results of Howell and Hiler (1975), is discussed in the next section.

Musick and Dusek (1971) plotted seasonal water use against yield in experiments with different water treatments conducted during 1963-1965 at the USDA Southwestern Great Plains Research Center at Bushland, Texas. From the scatter obtained, the lower yielding treatments can be represented by a linear relationship. The higher yielding treatments indicate that under conditions of good water management, the seasonal yield-water use curve is a curvilinear diminishing return relationship within the range of about 300 to 660 mm. The authors conclude that the function is not an explicit relationship but may vary considerably depending on various factors that affect both yields and water use. As will subsequently be shown, one of those factors relevant to their study may well be the amount of water lost below the depth of soil moisture measurement, in this case to 120 cm during the growing season and to 180 cm after planting and after harvest.

The analysis was expanded by Musick et al. (1976) who took the data collected by themselves and other researchers over the period 1956 to 1971 at Bushland and plotted relative grain yield against seasonal soil-water depletion from the 0 to 120 cm soil depth, as shown in Figure 6. Data were collected for grain sorghum, wheat and soybeans and a quadratic equation was fitted to all scatter diagrams with a high degree of success (coefficient of determination ranging from 0.57 to 0.99 for the 12 plots and being above 0.84 for 10 of them). In one case, however, the fitted curve was concave upwards and in nearly all cases a straight line would have fitted the data equally as well up to the point where maximum yield was first obtained, i.e., for the lowest amount of water depleted. Higher levels of seasonal depletion were achieved by irrigating to maintain a higher moisture content in the root zone and hence losses due to percolation beyond the 120 cm depth would be expected to be proportionally higher at the higher depletion levels.

In another series of experiments at Bushland and at the Texas A & M North Plains Research Field at Etter, Shipley and Regier (1975) and Shipley (1977) obtained curvilinear relationships between yield and applied water for corn, grain sorghum and wheat. Different yields were obtained for a given water quality, depending on the stage of growth during which the water was applied. By taking only the peak yield associated with a

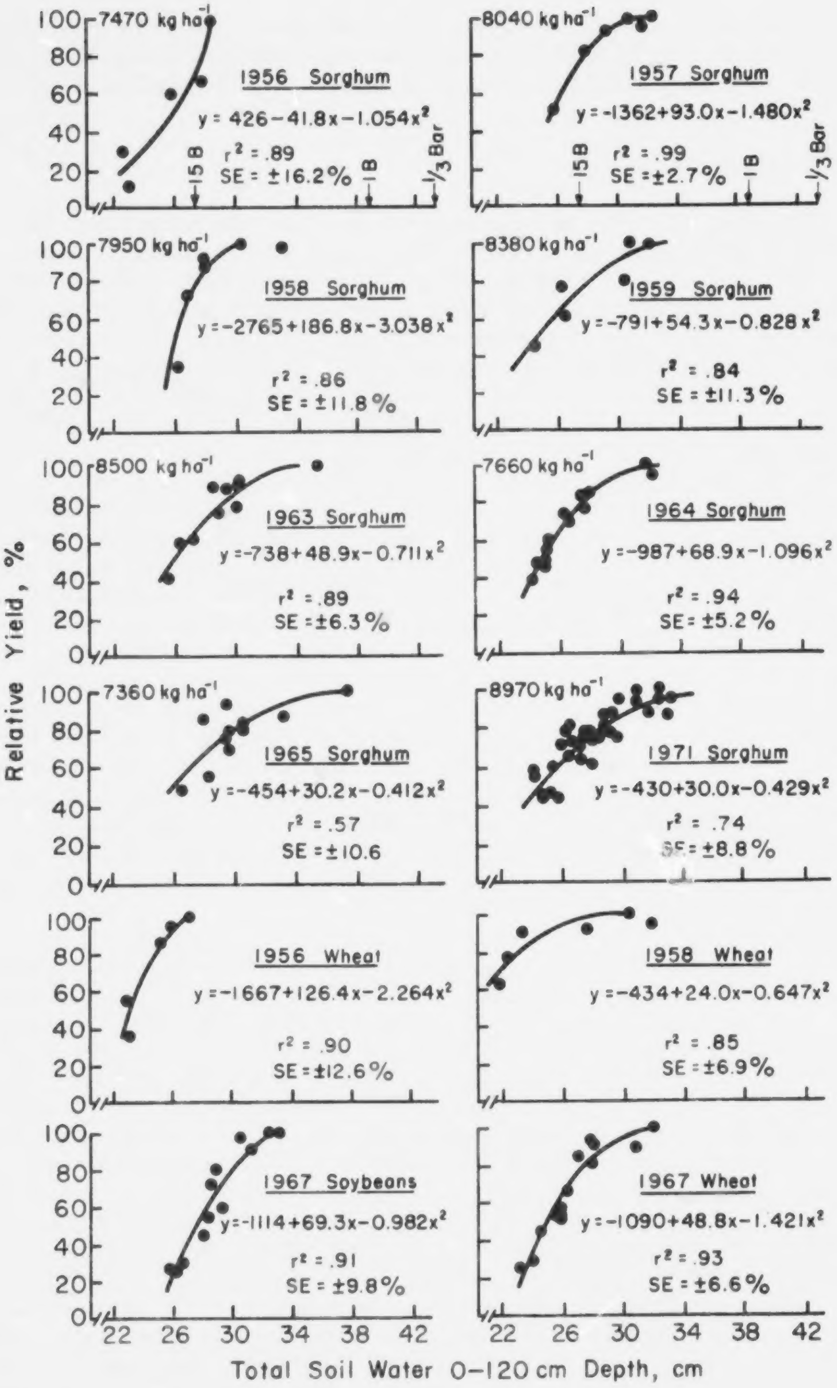


Figure 6. Relationship of soil-water depletion in the 0 to 120 cm depth to relative yield (from Musick et al., 1976).

given depth of application, a quadratic expression was able to be fitted to the results. This expression represented the optimum yield function and was used in subsequent analysis.

TIMING OF DEFICITS

The major factor contributing to the scatter in the results obtained by the many researchers is undoubtedly the timing of water deficits. Numerous investigators have shown that a water deficit occurring at one stage of growth will have a different effect on yield as compared with a deficit occurring at another stage. For the same amount of evapotranspiration, the yield may be expected to differ. For example, Robins and Domingo (1953) found that soil moisture depletion to the wilting percentage for one or two days during the tasseling or pollination period of corn results in as much as a 22 percent reduction in grain yield and periods of 6 to 8 days gave a yield reduction of about 50 percent. Yield reductions due to the absence of available water after the fertilization period appeared to be related to the maturity of the grain when the available water was removed. Following maturity, the depletion of the available soil moisture had no effect on yield. Denmead and Shaw (1960) found that corn subjected to moisture stress at silking was the most severely affected as far as grain yield was concerned. Moisture stress in the vegetative stage (prior to silking) reduced yield by 25 percent, moisture stress at silking reduced yield by 50 percent and moisture stress in the ear stage (after silking) reduced yield by 21 percent. Barnes and Woolley (1969) found a two-eared variety of corn more tolerant to moisture stress at pollination and blister kernel stages than a single-eared variety.

Downey (1972) found that a constant soil moisture stress tends to reduce the yield of nonforage crops almost as a linear function of the severity of the stress. When differential stress is applied, however, the effects are very much related to the timing of deficits. Severe water stress in corn during female meiosis (very early stage in the development of the grain), although for only a short period (8 days), dramatically reduced yield even though seasonal evapotranspiration was 90 percent of that giving maximum yield. A period of water stress following pollination and continuing until maturity also severely reduced the effectiveness of water applied in other growth stages. Yield was only about 50 percent of maximum even though ET was 90 percent of that giving maximum yield. On the other hand, water stress during male meiosis (or while the crop was young) increased water use efficiency. Downey concluded that if, of necessity, water is to be restricted, then it would be most desirable that it be restricted during the period of early growth.

From their work with grain sorghum, Howell and Hiler (1975) also concluded that the timing of the occurrence of a water deficit was more critical with regard to yield effects than the magnitude of the deficit. If a water deficit must occur, they suggest the bud through bloom period should be avoided and small water deficits occurring in several periods are preferred to a large deficit occurring in any single growth stage.

Similarly, Stewart et al. (1974) made a number of recommendations for managing water in corn production based on three years of research at Davis, California:

1. If there is to be a mild seasonal ET deficit (to 10 percent), it is best imposed wholly during the vegetative period. If that is not possible, the latter part of the grain period is nearly as acceptable. Avoid any deficit in the pollination period if there has been no deficit in the preceding vegetative period.

2. Moderate seasonal ET deficits (10-25 percent) must be distributed through at least two growth periods (one of which must be the vegetative period).

3. Severe seasonal ET deficits (25-50 percent) require distribution through all three major growth periods.

These recommendations for grain sorghum and corn are in general agreement with the conclusions of Salter and Goode (1967) who reviewed a wide range of literature. In addition, Salter and Goode have summarized research on the yield response to water at different stages of development for a wide variety of crops, ranging from cereal crops to orchards and from vegetable crops to flowers.

A number of researchers have observed that the yield response to a moisture deficit at a particular growth stage may not be a function of that growth stage alone, but may be affected by the degree of stress in earlier growth stages. There may be a tendency for stress imposed at any one stage to harden the plant against damage from stress at a later stage as far as grain yield is concerned (Denmead and Shaw, 1960). With corn and tomatoes, moderate soil water stress before flowering gave higher yields than did little or no soil water stress, when the post-flowering period was one of moderate water stress (Fischer and Hagan, 1965). Stewart et al. (1975) also found for corn that where there had been an earlier ET deficit in the vegetative period, the negative effect of a pollination period deficit was greatly blunted. The earlier water stress reduced plant size, and this appeared to "condition" the crop so that a following pollination period deficit had less negative effect on yield. The conditioning effect was not shown to operate on grain sorghum.

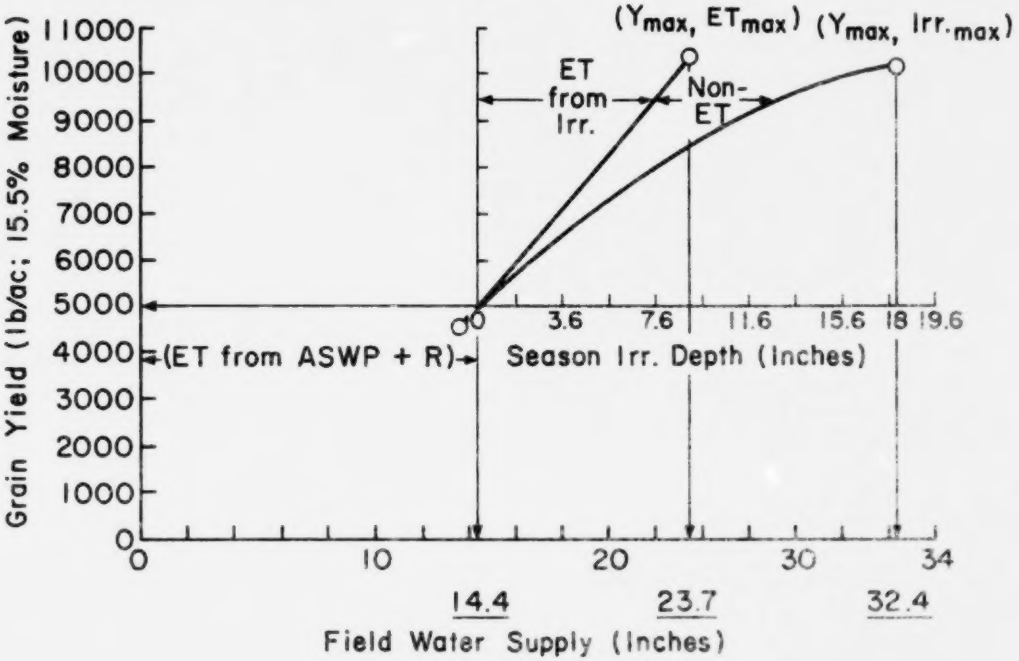
RESOLVING THE YIELD-WATER USE FUNCTIONAL RELATIONSHIP

In the literature reviewed above, a considerable amount of evidence has accumulated to indicate that, up to the minimum amount of ET producing the maximum yield, the relationship between yield and ET is linear. The correlation appears to be even higher when total dry matter is considered as compared to grain yields. The scatter in results using grain yields may be somewhat reduced when rainfall or other factors reduce stress during critical periods. Where severe stress is deliberately imposed during a critical growth stage, such as by Stewart et al. (1975) at Davis, a wider scatter may result.

However, two inconsistencies remain to be resolved: (a) to explain the results of those researchers who obtained a curvilinear relationship between yield and water use; and (b) to show how a unique relationship between yield and ET can hold when it is known that the same ET deficit can give different yields if imposed at different times, or conversely, how the same yield can be obtained for different values of ET.

The first problem is probably due to a combination of two causes. Firstly, when water is applied in excess of the amount required for maximum yield, "water use" and to some extent evapotranspiration, increases while yield remains constant or decreases. A decrease in yield is particularly apparent if waterlogging reduces soil aeration (Downey, 1972). This, coupled with the scatter of data due to the timing of deficits, allows a curvilinear function to be fitted to the plotted data. Secondly, in most cases, the abscissa is not evapotranspiration, but rather applied water or some similar parameter. In this case, the curvilinear nature of the function may be due to water losses incurred between water applied (or supplied) and the final use of some portion of that supply in evapotranspiration.

The difference between the two functions is well illustrated in Figure 7, in which the curved line represents the relationship between yield and the seasonal depth of irrigation water applied, or yield and field water supply (which includes available soil water at planting plus rainfall) and the straight line represents the relationship between yield and ET. The difference between the straight line and the curved line, shown as "nonET" on the figure, represents the water applied (or supplied) that is not consumed, i.e., losses. The convexity of the applied water function illustrates that these losses increase percentagewise as the point of fully satisfying ET demands is approached. The losses could be due to evaporation, surface runoff or deep percolation below the root zone. When Hillel and Guron (1973) took particular care to calculate the drainage component of the field water balance, the relationship between grain yield of corn and seasonal evapotranspiration was strongly linear.



Legend:

ASWP = Depth of Available Soil Water at Planting

R = Rainfall Depth

Irr. = Water Supplied by Irrigation

FWS = Field Water Supply

Figure 7. Relations between the Y versus ET and Y versus Irr functions, both set within Y versus FWS functional context which acknowledges and quantifies contributions of stored water and rainfall during season (from Stewart and Hagan, 1973).

The problem of developing a unique relationship between yield and evapotranspiration has received considerable attention from Stewart and associates at Davis. They recognized that irrigation programming registers a dual effect on yield (Stewart and Hagan, 1973). The first effect is inevitable, the second is manageable. The primary effect is that of water shortage, per se. Thus, any seasonal ET deficit is inevitably associated with some minimum fractional reduction in yield below maximum. A secondary reduction in yield may result from the timing of the ET deficits, with those occurring during more sensitive or "critical" growth stages of the crop in question causing a relatively larger decrease in yield. Such losses are avoidable through informed water management, which has the effect of orchestrating the sequence of ET deficits so that yield loss is minimized (Stewart et al., 1976). The Davis experiments have shown that when ET deficit sequencing is optimal (i.e., any deficits are timed so that they cause the least possible reduction in crop yield), the relationship between yield and seasonal ET is quite well represented by a straight line function for corn, grain sorghum, and pinto beans. If the upper bound of yield is related to the depth of water applied, rather than ET, a curvilinear relationship will result.

PREDICTIVE MODELS

Many attempts have been made to develop a functional relationship between yield and water inputs, taking into account the different effects on yield of water deficits at different stages of growth. Moore (1961) developed a model to allow calculation of the net variable income associated with each irrigation cycle, allowing calculation of the optimal time to apply irrigation water. Moore used as a basis for this analysis a hypothetical relationship between the relative rate of plant growth and the mean soil moisture stress in the active root zone, shown in Figure 8 for different soil types. For one irrigation cycle, relative growth is the area under the moisture release curve (relative growth rate versus soil-water depletion):

$$Gr_i = I_{\theta_i} \quad \ldots\ldots\ldots\ldots \quad (5)$$

where Gr_i is the relative growth during the i^{th} irrigation cycle expressed as a percent of potential growth, or

$$Gr_i = \frac{\int_0^{\theta_i} g(x)\,dx}{\theta_i \times 100} = I_{\theta_i} \quad \ldots\ldots\ldots\ldots \quad (6)$$

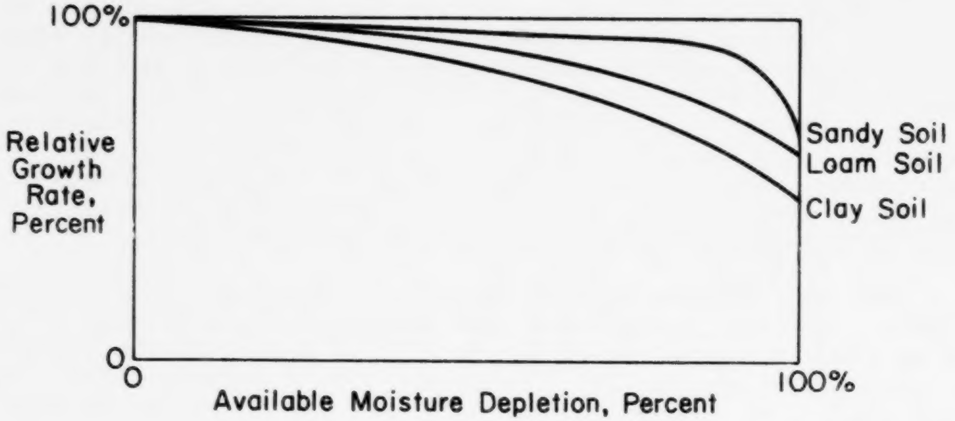


Figure 8. Variation in relative growth with available moisture depletion for sandy, loam and clay soils (from Moore, 1961).

where I_{θ_i} is the fraction of potential growth for one irrigation cycle, θ_i is the moisture depletion percent at which the irrigation cycle is terminated and g(x) is the functional relationship of relative growth to percent moisture depletion.

For an entire irrigation season,

$$Gr = \sum_{i=1}^{n} I_{\theta_i} \frac{t_i}{T} \quad \ldots\ldots\ldots\ldots\ldots\ldots (7)$$

where t_i is the length in days of the i^{th} irrigation cycle and T is the length in days of the irrigation season.

For the special case where θ_i is constant for each irrigation cycle throughout the season,

$$Gr = I_{\theta_i} \left(\sum_{i=1}^{n} \frac{t_i}{T}\right) = I_{\theta_i} \quad \ldots\ldots\ldots\ldots (8)$$

because for the entire season,

$$\sum_{i=1}^{n} \frac{t_i}{T} = 1 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (9)$$

Moore recognized the need for further refinement in the method, especially in regard to the nature of the effect of different amounts of soil moisture stress at different time periods upon production of different plant parts and the effect of moisture stress on the different stages of plant development. However, the model allowed him to proceed with the economic analysis of the value of irrigation water applied within any one irrigation cycle and to determine an optimal irrigation program which could bring into account varying water prices and changing commodity prices during the growing season.

Hall and Butcher (1968) sought to develop a method which could be used to assure that the seasonal distribution of water was optimal (within the accuracy of the data and the postulates) for each point on the overall production function. The authors recognized that the magnitude of crop yield reductions due to a soil moisture deficiency may depend almost as much on when the soil moisture deficiency occurs as it does on the total magnitude of the seasonal shortage. They postulated that if Y_{max} is the maximum yield of a crop under given conditions and if the soil moisture is kept at field capacity, w_f, through all growth periods of the crop, then the yield would be Y_{max}. However, if the soil moisture fell to a value w_i less than w_f during the i^{th} growth period only, but remained at w_f for all other growth periods, then the resulting yield, y, could be expressed as:

$$y = a_i \, Y_{max} \quad . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \quad (10)$$

which defines a_i under the condition of the postulate. As a_i depends on the magnitude of the soil moisture content, w_i, it may be expressed as $a_i = a_i(w_i)$. The authors then postulate, for the given conditions, that the yield to be expected when two or more of these time periods have deficiencies can be calculated by the multiplicative function:

$$y = a_1(w_1) \cdot a_2(w_2) \cdot a_3(w_3) \ldots a_n(w_n) \; Y_{max} \quad . \; . \; . \; . \; . \quad (11)$$

The authors proceeded to the development of the methodology for optimal irrigation timing, using this expression as the objective function of a dynamic programming problem (maximize y) subject to the constraints of water supply, allowable soil moisture levels (wilting point to field capacity) and water balance in the root zone.

Jensen (1968) related yields to the effects of limited soil moisture (resulting in reduced water use during a growth stage) on the depvelopment of the marketable product of a determinate flowering crop, by the multiplicative expression:

$$\frac{y}{Y_{max}} \simeq \prod_{i=1}^{n} \left(\frac{ET}{ET_p}\right)_i^{\lambda_i} \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (12)$$

where y/Y_{max} represents the relative yield of the marketable product from an agricultural crop; $(ET/ET_p)_i$ represents the relative total evapotranspiration during a given stage of physiological development (ET is the actual use of water and ET_p is the use of soil moisture was not limiting) and λ_i represents the relative sensitivity of the crop to water stress during the growth stage i. The right side of the equation is a product. Therefore, severe water stress, as indicated by reduced water use, during a single growth stage could reduce the yield of the marketable product severely. The magnitude of λ for specific growth stages would depend primarily on the sensitivity of plant growth to water stress during each growth period. The primary implication of the model is that the yield of the marketable product of a farm crop may not be linearly related to total water use when plants are stressed.

The Stress Day Index Model (Hiler and Clark, 1971) is an additive type expressed as:

$$\frac{y}{Y_{max}} = 1.0 - \frac{A}{Y_{max}} \sum_{i=1}^{n} [CS_i (1.0 - \frac{ET}{ET_p})_i] \quad \ldots \quad (13)$$

where CS_i is the crop susceptibility factor which expresses the fractional yield reduction resulting from a specific water deficit occurring at growth stage i. A is the yield reduction in kilograms per hectare per unit of Stress Day Index (SDI), where:

$$SDI = \sum_{i=1}^{n} (SD_i \times CS_i) \quad \ldots\ldots\ldots\ldots\ldots \quad (14)$$

and SD is the stress day factor which expresses the degree of water deficit in the specific growth stage:

$$SD = (1.0 - \frac{ET}{ET_p}) \ldots\ldots\ldots\ldots\ldots\ldots \quad (15)$$

The crop susceptibility factor (CS) is a function of the deficit factor. This functional relationship has not been postulated but has been taken as linear based on other research. If CS is assumed to be a linear function of the deficit,

$$CS = a\left(1.0 - \frac{ET}{ET_p}\right) \quad . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \quad (16)$$

then, the original equation can be written (Howell and Hiler, 1975) as:

$$\frac{y}{Y_{max}} = 1.0 - \frac{A}{Y_{max}} \sum_{i=1}^{n} \left[a_i\left(1.0 - \frac{ET}{ET_p}\right)_i^2\right] \quad . \; . \; . \; . \quad (17)$$

Yaron and Strateener (1973) developed a soil moisture simulation model based on evapotranspiration predictions. Using wheat data, the authors fitted parameters to a Cobb-Douglas type function, an exponential function and a Mitscherlich function. The last gave the most reasonable yield estimate obtainable under optimal conditions and was chosen as the "best estimate" and as the basis for the analysis of optimal irrigation policy.

The Mitscherlich equation is:

$$y = Y_{max} \prod_{i=1}^{n} \left(1 - B_i e^{-k_i x_i}\right) \quad . \; . \; . \; . \; . \; . \; . \; . \; . \; . \quad (18)$$

where y is the yield, Y_{max} is the maximum yield, i is an index of the growth stage $(i=1,...,n)$, x_i is a dimensionless soil moisture index and B_i and k_i are parameters (Blank, 1975).

Another single crop model was presented by Minhas et al. (1974), who first developed an evapotranspiration prediction model for wheat as a function of available soil moisture only. The function was of the form:

$$f(x) = (1 - e^{-rx})/(1 - 2e^{-r\bar{x}} + e^{-rx}) \quad . \; . \; . \; . \; . \; . \; . \quad (19)$$

where r is a parameter fitted from the data, x is the available soil moisture (ASM) in the root zone, $\bar{x}$ is the ASM at field capacity and f(x) is the ratio of actual to potential ET. Actual ET is then the product of f(x), potential ET and an assumed scaling factor which varies with the maturity of the crop. Parameters were fitted using wheat data from Delhi, India, and tested against alfalfa data reported in 1968 by Mustonen and McGuiness (Minhas et al., 1974).

With an adequate ET prediction function, the authors used regression to fit parameters to the multiplicative function:

$$y = a[1-(1-x_1)^2]^{b_1}[1-(1-x_2)^2]^{b_2}\ldots[1-(1-x_n)^2]^{b_n} \qquad (20)$$

where y is the yield and x_j is the relative evapotranspiration in period j. The parameters a and b_j are fitted from data.

Hanks (1974) developed a simple model, based on earlier models, for both dry matter yield and grain yield, with the main emphasis on the former. The equation to relate dry matter yield, y, to transpiration is taken from that of de Wit (1958):

$$y = mT/E_o \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (21)$$

where T is transpiration, E_o is average fresh water evaporation rate and m is a crop factor. This equation had been confirmed by Hanks et al. (1969). Four different methods of relating T to T_p (potential transpiration) were used in verifying the model, all giving reasonable results. Soil evaporation (E_s) is assumed to be related to potential soil evaporation (E_{sp}) and the time since last wetting (t) by the empirical relation:

$$E_s = E_{sp}(t_p/t)^{1/2} \quad \ldots\ldots\ldots\ldots\ldots \quad (22)$$

where t_p is the time when $E_s = E_{sp}$ (assumed one day). The potential transpiration, T_p, is calculated from:

$$T_p = ET_p - E_{sp} \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (23)$$

To estimate grain production, Hanks used the method of Jensen (1968) which has been described above.

Stewart et al. (1976) developed two models which utilized estimates of anticipated ET deficits and growth stage sensitivities to predict actual ET and yield for the season. The models were developed for pinto beans, but the authors consider them to have equal applicability to both grain sorghum and corn.

Model 1 (Stewart et al., 1976) is referred to as the Growth Stage Model and is given by the additive expression:

$$y = Y_{max} - Y_{max}\sum_{i=1}^{n} YRR_i\left(\frac{ET_{M_i} - ET_{A_i}}{ET_M}\right) \quad \ldots\ldots \quad (24)$$

where ET_M is the total ET requirement for the season, ET_{M_i} is the ET requirement for growth period i, ET_{A_i} is the actual ET in growth period i and YRR_i is the yield reduction ratio in growth period i, defined as the ratio of percent yield reduction to percent ET deficit.

Model 2 is referred to as the ET Deficit Sequence Model and is expressed as:

$$y = Y_{max} - Y_{max}\left[\beta_o\left(\frac{ET_M - ET_A}{ET_M}\right) + (\beta - \beta_o)\left(\frac{ET_M - ET_A}{ET_M}\right)\right] \quad . \; . \; (25)$$

where β_o is the yield reduction ratio, where ET deficit sequencing is optimal, and β is the yield reduction ratio predicted for the season, based on the actual ET deficit sequence and on the growth period sensitivities found by research. Obviously, the expression in brackets may be simplified. However, the first term in the brackets represents the inevitable yield loss and the second is the additional loss due to suboptimal ET deficit sequencing. The authors consider this separation of the yield losses to give Model 2 an advantage over Model 1.

The eight crop production functions described above have been presented as a review to acquaint the reader with the divergent approaches to predicting the anticipated yield from a given quantity of water. The basis for development of the various models range from data collected from extensive field trials to some rather questionable assumptions.

Yaron and Strateener (1973) and Minhas et al. (1974) rely on data from a number of years to establish their production functions. Howell and Hiler (1975) tested the model of Minhas et al. and those of Jensen (1968) and Hiler and Clark (1971) on a limited amount of data from a variety of sources and found that all of the models, which are quite similar in formulation, represented the experimental data accurately within the range of data. Hanks (1974) found that his model gave a good fit of predicted versus measured dry matter yield of sorghum in Colorado, corn dry matter and grain yields in Israel and corn grain yields in Nebraska, with various water application treatments. The Stewart et al. (1976) models were developed from data collected at Davis, California, and await independent verification. The Moore (1961) model and the Hall and Butcher (1968) models were developed from theoretical considerations and would appear difficult to apply.

The functions described herein are about evenly divided between multiplicative type functions and additive type functions. Both cannot be correct for a given situation. The multiplicative function indicates, for example, that if growth is only 70 percent of potential for a particular growth stage, then the maximum yield attainable by the crop is 70 percent of potential. According to the additive theory, 70 percent of potential growth in a particular time period would only result in potential yields being reduced by 30 percent of that particular time period's potential contribution. The overall reduction would be considerably less if there were a number of time periods considered.

Multiplicative functions meet two important conditions that exist in the relationship between actual yield and moisture availability. Firstly, if the soil moisture during all stages of growth is at field capacity, or evapotranspiration is at the potential rate, then there is no stress and yield equals Y_{max}. Secondly, if soil moisture is entirely depleted, or evapotranspiration ceases in any growth period, then the plant dies regardless of the moisture regime in other growth stages and yield equals zero. This condition is usually not met by an additive function.

The multiplicative function, however, may break down when stress occurs in a number of growth stages. For example, if a yield reduction of 0.8 occurs due to stress in an early growth stage alone, the final yield is $y = 0.8\ Y_{max}$. If a yield reduction of 0.6 occurs due to stress in a later growth stage alone, $y = 0.6\ Y_{max}$. If, in another experiment, the crop receives these respective amounts of stress in both growth stages, with no stress in other growth stages, the anticipated yield according to the multiplicative theory would be $y = 0.48\ Y_{max}$. However, experiments with some crops have revealed a conditioning effect as discussed earlier and so the actual reduction in yield would not be as great as shown here. The conditioning effect is not taken into account by the mulitplicative functions discussed above, and these may be expected to underestimate yields where conditioning occurs.

The development of crop production functions cited above, and by other researchers not cited, has been stimulated by the desire to achieve the objectives outlined at the beginning of this section. The process has been to develop a production function for use in determining the optimal irrigation program, the optimal irrigated area, or whatever objective is desired. For the case of researchers such as Jensen (1968), Hiler and Clark (1971) and Stewart et al. (1976) the production function has been developed separately. Other researchers, such as Moore (1961) and Hall and Butcher (1968), have developed the production function en route to developing the methodology for optimal irrigation programming. As stated by Minhas et al. (1974), the exact shape of the crop production function must be known before the question of economically optimal use of water can be resolved. The point is made by Blank (1975) that an adequate theory is not generally accepted and that currently available data are not sufficient to conclusively adopt any of the production functions described. In other words, the endeavors of researchers to develop optimal irrigation programs and allocations (i.e., Dudley et al., 1971a, 1971b), while providing valuable insight into the physical processes, will find little application until the form of the crop yield-water use function is known more precisely.

Section 5

EXPERIMENTAL DESIGN

PURPOSE OF EXPERIMENT

The literature reviewed in the preceding section has revealed an apparent dichotomy in the form of the relationship expressing crop yield-water functions. The difference between the forms of the relationship would appear resolved by taking into consideration the measure of water used in the abscissa. Researchers plotting yield against applied water generally obtain a concave downwards function. The advent of more advanced research tools, particularly the neutron probe for soil moisture measurement, has allowed recent researchers to plot yield against ET, obtaining a linear upper bound on the results.

The purpose of this experiment was to confirm whether the results of the recent researchers could be substantiated. One year of experimental results could not be expected to provide sufficient data on which to base extensive conclusions regarding optimal water allocation. However, if the data gave markedly different results from the limited experimental data available, the universality of the published data would be open to question. On the other hand, if the data conformed to that obtained by the other researchers, it would appear reasonable to extend their results to different areas. This experiment was conducted in a manner which would allow comparison with published results. Where possible, the yield of both grain and dry matter was obtained.

DESCRIPTION OF PLOTS

The plots used for the field trials are located on a 23-acre (9.3 hectare) area of leased land situated to the north of Grand Junction, Colorado. The farm is bounded on the north by the Government Highline Canal and on the east by a natural channel known as Indian Wash (Figure 9).

The location of the water supply lateral running through the farm divides it into three sections (Figure 10). In 1976, alfalfa was grown in Field I, corn in Field II, wheat in the northern section of Field III and José Tall Wheatgrass in the

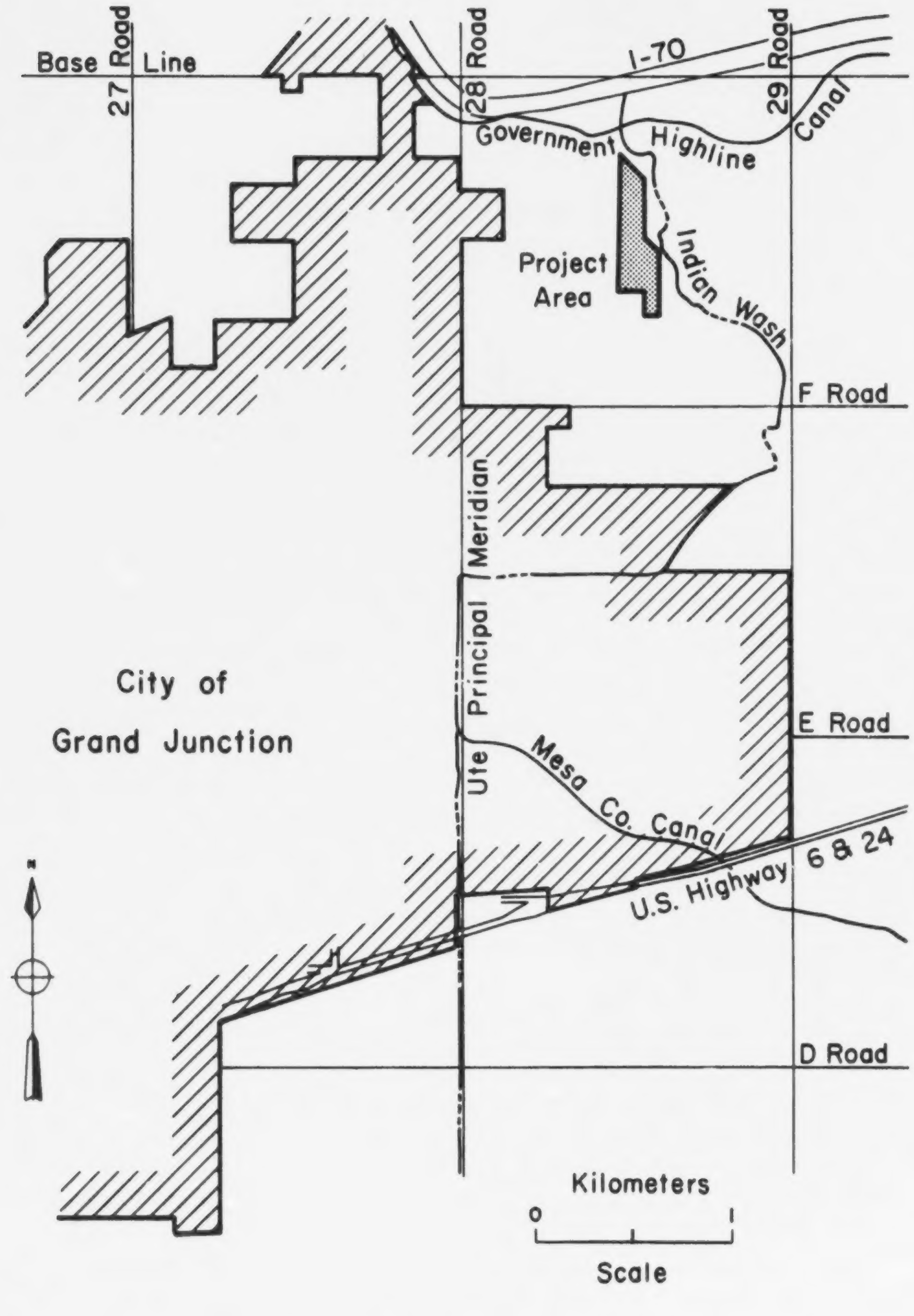

Base Line
27 Road
28 Road
29 Road
I-70
Government Highline Canal
Project Area
Indian Wash
F Road
Ute Principal Meridian
City of Grand Junction
E Road
Mesa Co. Canal
U.S. Highway 6 & 24
D Road
Kilometers
0
1
Scale

Figure 9. Location map of the project area.

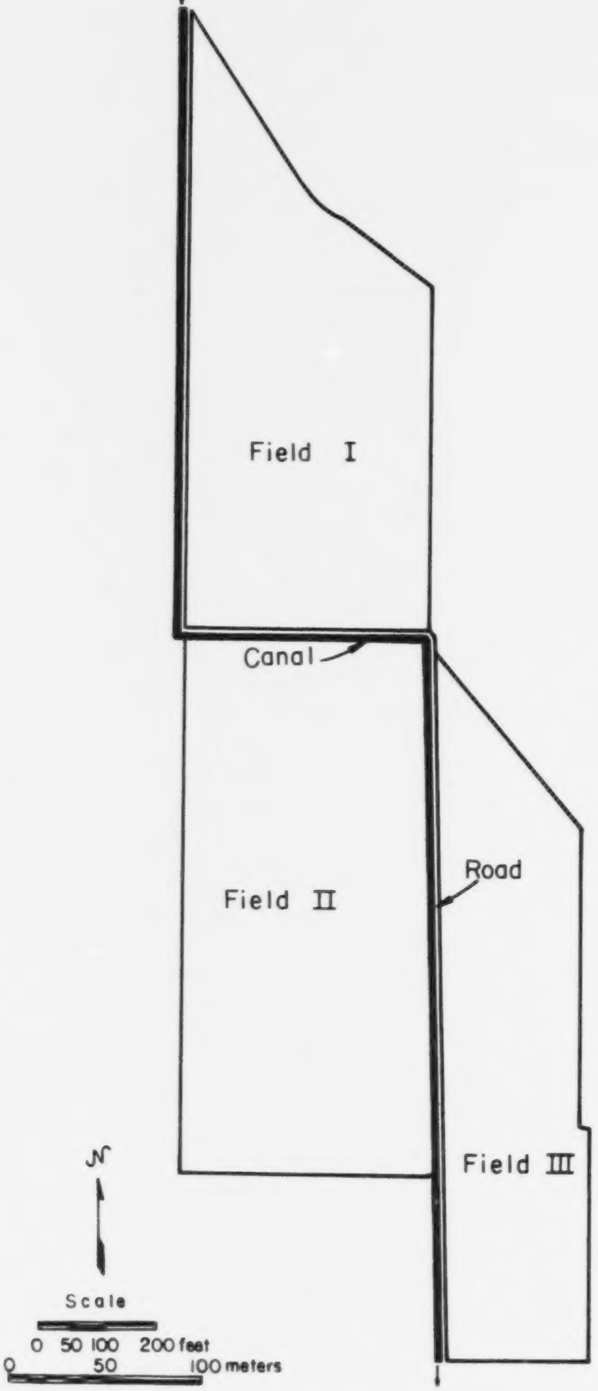

Field I
Canal
Field II
Road
Field III
N
Scale
0 50 100 200 feet
0 50 100 meters

Figure 10. Map of the Matchett Farm fields used for the study area.

southern section of Field III. Field I consisted of 16 plots, Field II of 32 plots and Field III contained 10 plots of wheat and 5 of wheatgrass. The location of the plots within each field is shown on Figures 11, 12 and 13.

Because of the particular requirements of earlier experiments at the farm, not all plots are of equal size. Plots in Fields I and II are all nominally 100 feet by 100 feet (30.5 by 30.5 meters) while Field III consists of 6 plots of 100 feet by 100 feet, 2 of 200 feet by 40 feet (61 by 12 meters), 2 of 300 feet by 40 feet (91.5 by 12 meters) and 5 of 500 feet by 40 feet (152 by 12 meters). (English units are used here as these were the units used during construction.)

Water supply to the plots came from the lateral mentioned above. The water was diverted into aluminum main supply lines running north-south along the western edge of Fields I and III and the eastern edge of Field II. From the main supply line the water was measured through V-notch weirs into gated pipe running east-west across the top of each row of plots. In the case of Field II, the water was first pumped from the lateral into an elevated tank to provide sufficient head to fill the gated pipe.

The ground surface of the farm slopes to the south and the whole area is underlain by Mancos Shale generally 2 to 4 meters below the surface, with isolated areas as shallow as 0.4 meters and as deep as 7 meters. The shale generally dips to the southwest with some undulation. The plots were formed by excavating a trench along the lines dividing the plots to a depth slightly below the top of the shale. A plastic curtain was then placed vertically in the trench to divide the individual plots. The lower edge of the curtain was sealed to the shale by backfilling to the original elevation of the shale with compacted clay. A drainline, encased in a gravel filter material, is located inside the curtain (Figure 14) and is continuous around the plot. The curtain was raised vertically to within approximately a meter of the ground surface and held in place by backfilling with the excavated material. Water entering the drainline leaves the plot area via solid pipeline which transports it to a measuring station where quantity and quality can be monitored.

SOIL CHARACTERISTICS

Soils on the experimental farm are, in general, silty clay loams derived from the underlying Mancos Shale. Some variation in the profile exists, with a layer of more sandy textured soil being encountered in many plots about half a meter below the surface. Sandy layers, where encountered, are generally from a few centimeters to one-half a meter thick.

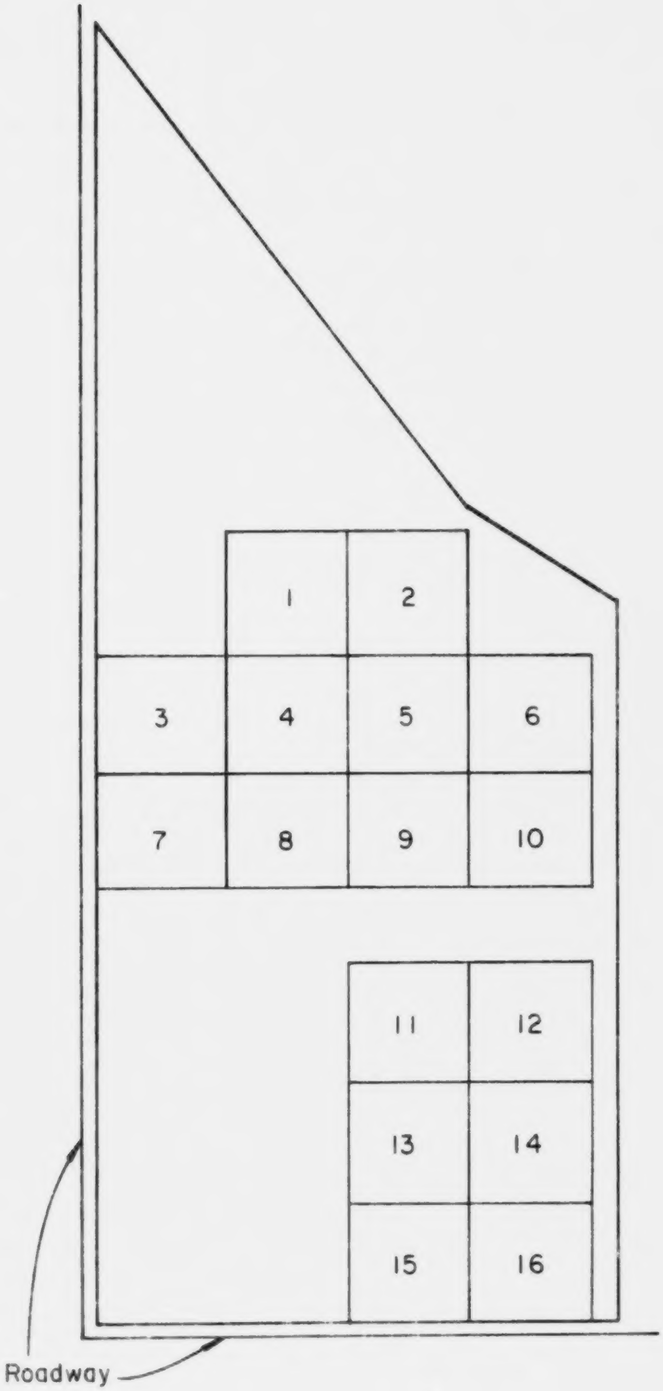

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
Roadway

Figure 11. Location of plots in Field I.

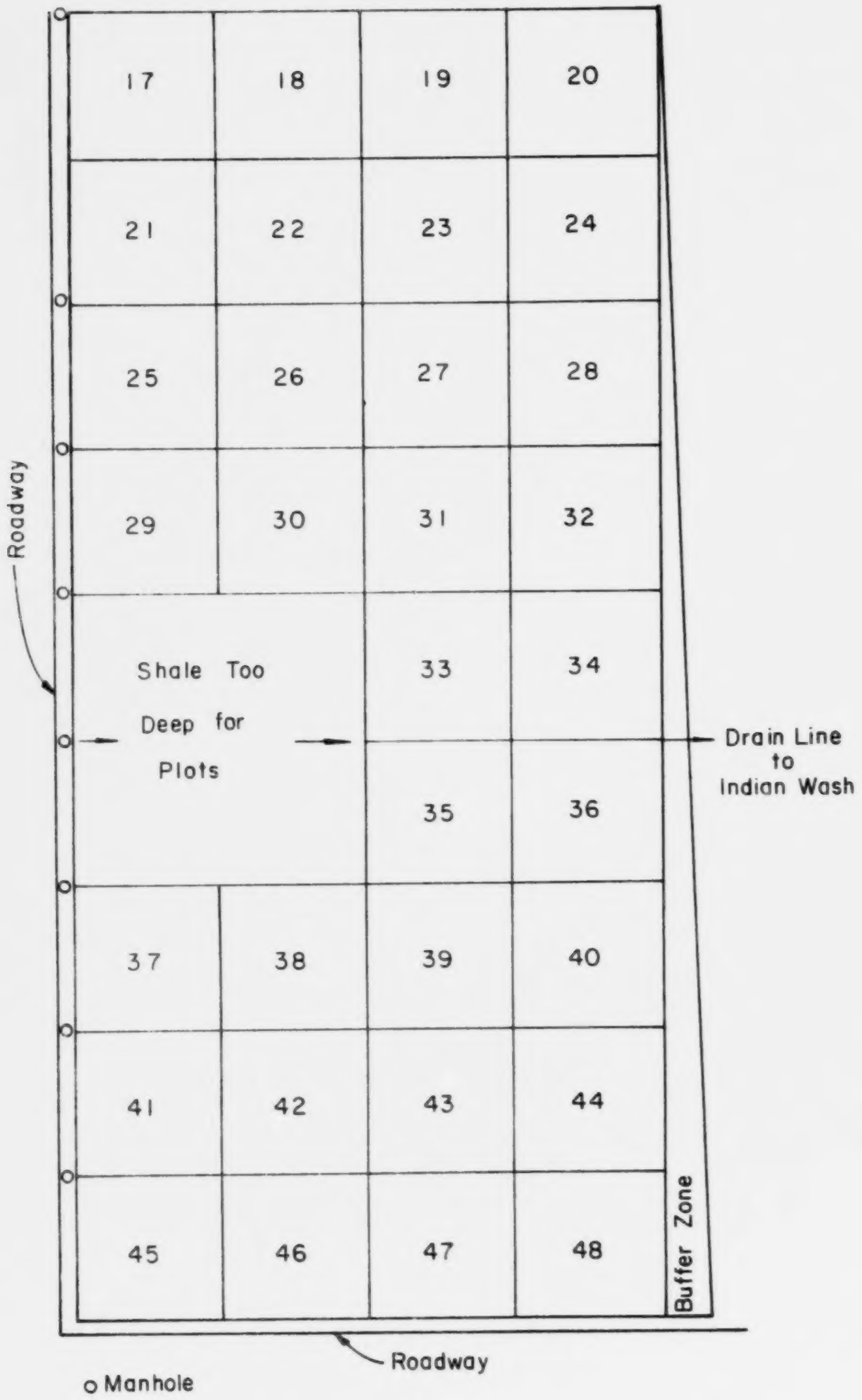

17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
Shale Too Deep for Plots
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
Roadway
Drain Line to Indian Wash
Buffer Zone
Roadway
o Manhole

Figure 12. Location of plots in Field II.

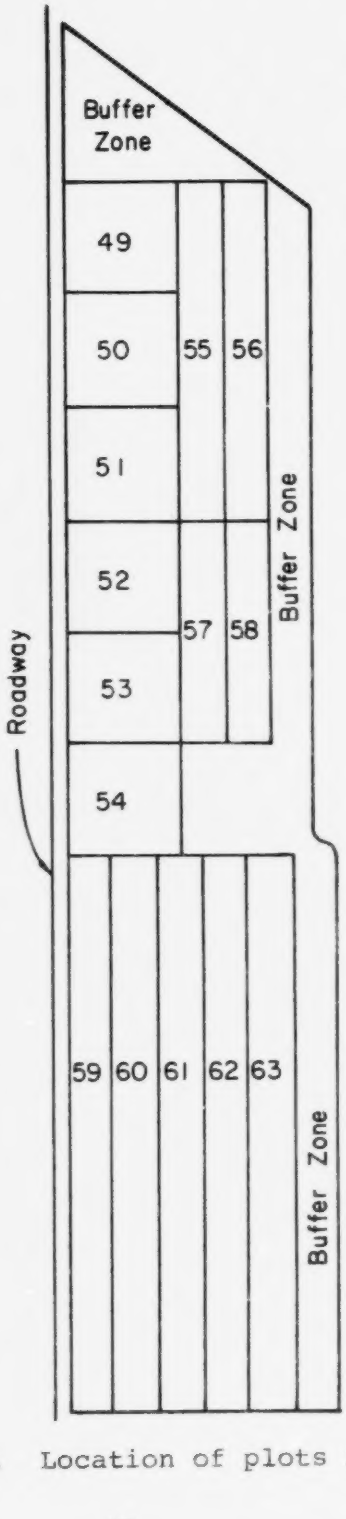

Buffer Zone
49
50
51
52
53
54
55
56
57
58
Buffer Zone
Roadway
59
60
61
62
63
Buffer Zone

Figure 13. Location of plots in Field III.

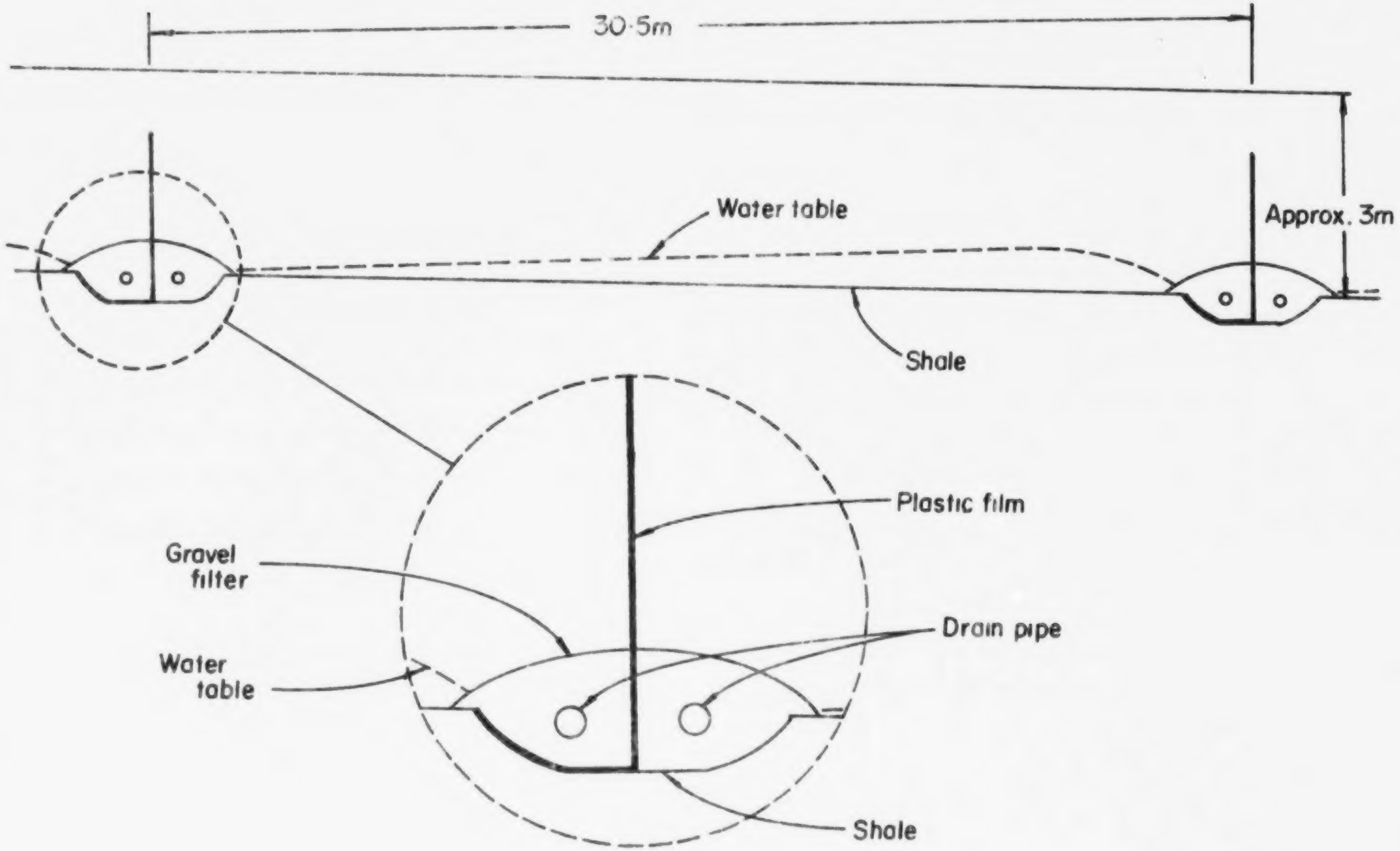

30·5m
Water table
Approx. 3m
Shale
Plastic film
Gravel filter
Drain pipe
Water table
Shale

Figure 14. Plot cross-section with drain details.

During the course of construction in 1973, the soil surface was heavily compacted. This severely hampered cultural and irrigation activities during the first two seasons particularly, and areas that were heavily trafficked were still found to have very low infiltration rates in 1976.

Bulk densities are quite high for the soil type, averaging 1.45 gm cm^{-3} in the plow layer and 1.55 gm cm^{-3} deeper. The moisture retention characteristics of the soil vary slightly from plot to plot and with depth. The water content at field capacity (one-third bar pressure) is about 37 percent by volume. The saturation water content is about 45 percent (Ayars, 1976). Wilting point (15 bar pressure) is about 20 percent by volume.

As mentioned in the preceding section, the depth from the soil surface to the underlying shale bedrock varied markedly. A map showing the contours of the depth to shale from the ground surface is presented in Figure 15.

The desert climate of the area has restricted the growth of native vegetation, thereby causing the soils to have a low nitrogen content due to the absence of organic matter. The mineral soil is high in bicarbonate and sulphate salts of sodium, potassium, magnesium and calcium. Although natural phosphate exists in the soils, it becomes available too slowly to supply the needs of cultivated crops. Other minor elements such as iron are available (Ayars, 1976).

Salinity levels vary over the farm. In order to analyze any possible effects on yield, samples were taken from each plot for salinity analysis. Soil samples were collected from 19th through 22nd of July, using a soil "King" tube to a depth of 120 cm. A sample composited of four soil cores was taken from the harvest rows of each plot. The electrical conductivity of the saturated extract and the pH of each sample was determined. The conductivity of the saturated extract ranged from 1.5 to 5.5 millimhos per centimeter, the average being around 3. The pH ranged from 6.6 to 7.8 and averaged 7.2. The sodium adsorption ratio was determined from samples collected during the preceding winter to be about 2.

IRRIGATION REGIME

The greatest latitude for experimentation was with the corn in Field II which was sown and harvested within the period under the authors' control. Experimentation with different irrigation regimes was carried out with the alfalfa, but the experiment was ultimately abandoned as the effects of different treatments in earlier years and in preceding cuttings carried over. The watering schedule of the wheat was out of the authors'

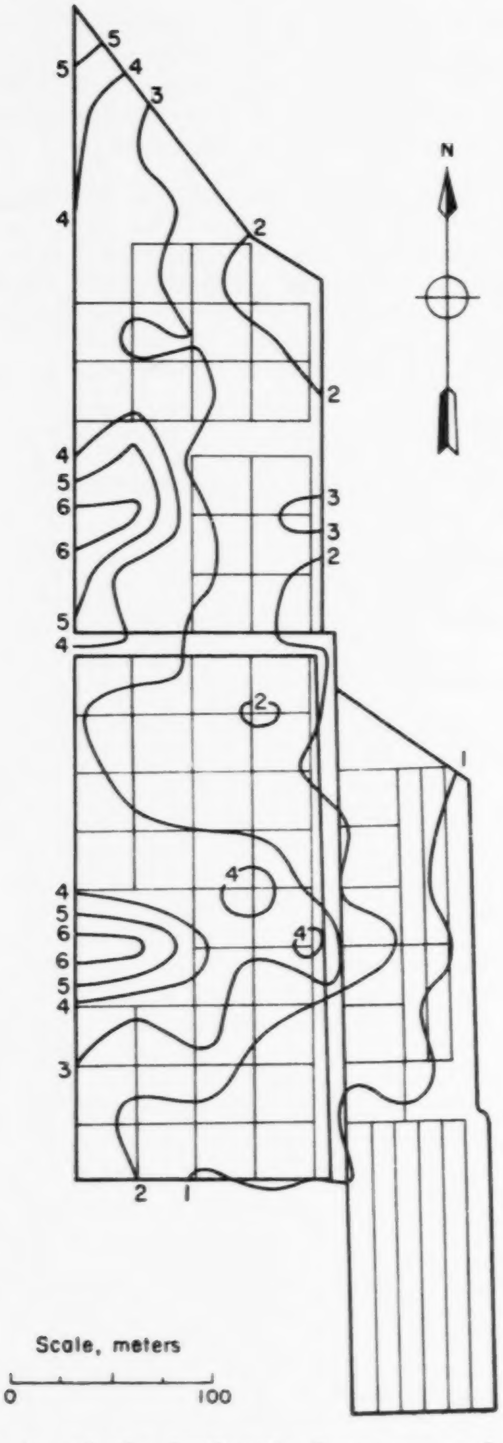

N
5
5
4
3
4
2
2
4
5
6
6
5
4
3
3
2
2
1
4
4
4
5
6
6
5
4
3
2
1
Scale, meters
0
100

Figure 15. Depth to shale bedrock from ground surface, in meters.

control until mid-May 1976, by which time the effects of early spring moisture stress were evident.

Field II was watered as a single unit over the period 3rd-10th May, following sowing. The gated pipes were then installed across the top of each row of plots. Over the period 8th-11th of June, when the corn was approximately 15 to 20 cm high, all of the plots were individually irrigated again with approximately a 45 mm watering.

The corn was then differentiated in three subsequent growth stages. Stage I was from the emergence and establishment stage through the main period of vegetative growth preceding tasseling. Stage II was the pollination period from tasseling to the blister kernel stage, and Stage III was the grain filling period from blister kernel to physiological maturity. These growth stages coincide with those of Stewart, et al. (1975) although some subjectivity is involved in the differentiation between growth stages.

Water was applied to the corn weekly during one, two or three of the growth stages, giving eight different treatments (Figure 16). Each treatment was replicated four times. The eight plots within a replication were grouped contiguously to provide approximately equal depth to shale within the replication.

Those plots being watered within a growth stage were watered once a week with a net amount calculated to be slightly in excess of the crop requirements. Thus, in the early stages it was planned that the watered plots would receive approximately 40 mm per week, rising to 65 mm per week during the period of peak demand. Stressing during a particular growth stage was achieved by eliminating all irrigation from the stressed plots during that growth stage. Rainfall which fell during the growing season was light and infrequent, allowing a high degree of stress to be applied.

The wheat plots were similarly differentiated according to growth stage, although to a somewhat limited scale due to experimental work with the wheat not beginning until the spring following its winter dormancy. All plots were watered during the week beginning 17th of May, when in the late boot stage, after which two growth stages were considered, the anthesis period and the grain filling period. Three plots received water only during the first stage (I-0), two plots received water only during the second stage (0-I), three plots received water during both stages, (I-I), and two plots received no water at all during both of these stages (0-0). Approximately 50 mm (net) of water was applied per week to those plots being irrigated.

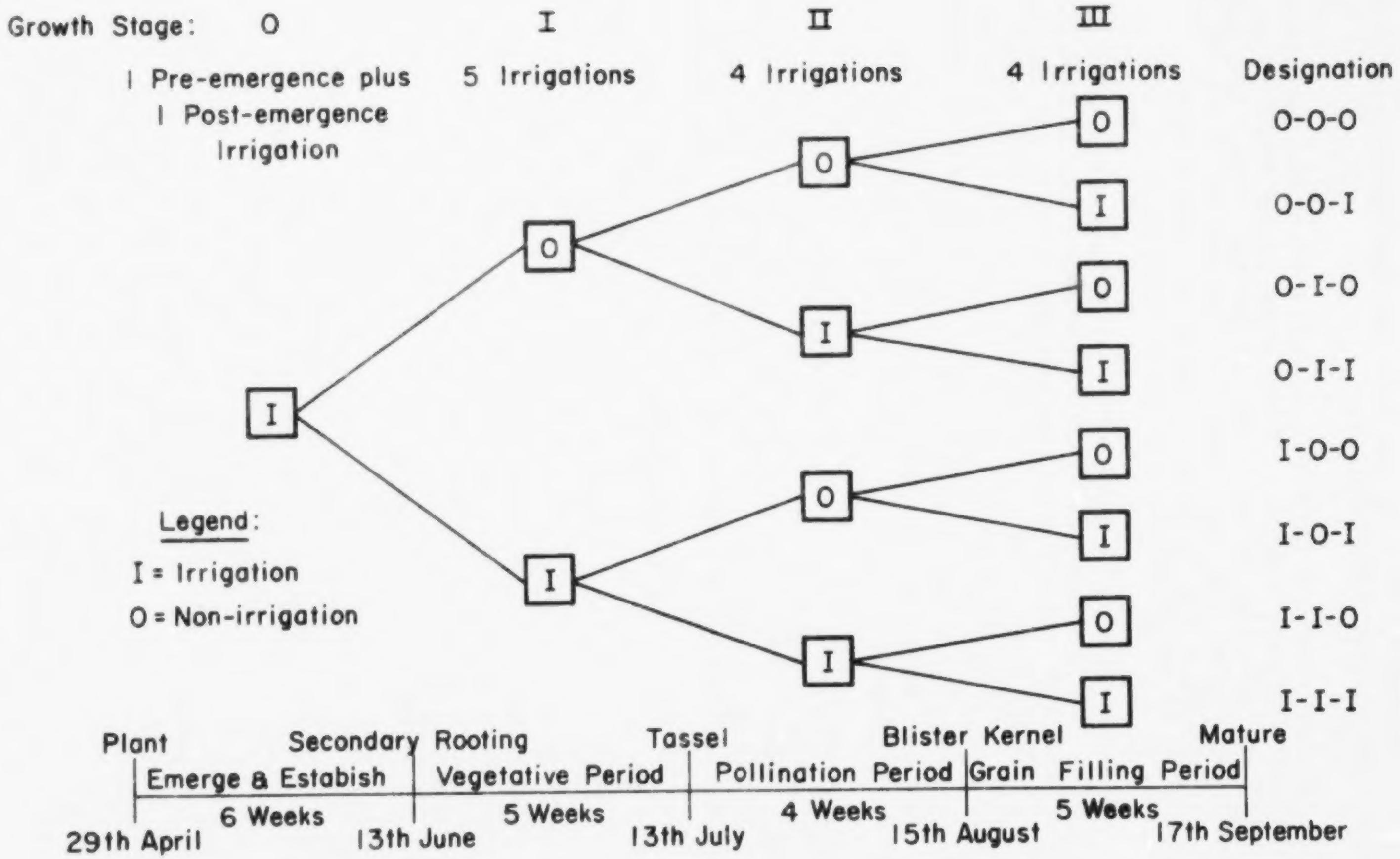

Growth Stage: O
I
II
III
1 Pre-emergence plus
1 Post-emergence
Irrigation
5 Irrigations
4 Irrigations
4 Irrigations
Designation
O-O-O
O-O-I
O-I-O
O-I-I
I-O-O
I-O-I
I-I-O
I-I-I
Legend:
I = Irrigation
O = Non-irrigation
Plant
Secondary Rooting
Tassel
Blister Kernel
Mature
Emerge & Estabish
Vegetative Period
Pollination Period
Grain Filling Period
6 Weeks
5 Weeks
4 Weeks
5 Weeks
29th April
13th June
13th July
15th August
17th September

Figure 16. Irrigation treatments for corn.

FERTILIZER TREATMENTS

Following the 1975 crop, the fertility level was determined by compositing samples from paired adjacent plots and fertilizer was applied that autumn at the rates shown in Table 1. These rates were chosen on the basis of an alternative experimental design which was ultimately abandoned. Subsequently, nitrate levels for each plot were determined during the season by plant leaf analysis.

The fertilization treatments were designed to ensure a good stand of the crop and to evaluate nutrient losses due to excess irrigation. Field II was the principal study area for fertilization studies. The corn grown in this field was fertilized to obtain two levels of nitrogen. The alfalfa, wheat and José Tall Wheatgrass grown in the remaining plots were fertilized uniformly based on nutrient analysis of the surface soils.

Alfalfa was grown in Field I and was fertilized initially with phosphate to establish the crop and was again fertilized with phosphate in subsequent years to maintain its vigor. The fertilization was done uniformly over the entire field.

The wheat crop, Field III-N, received the recommended quantities of nitrogen, potassium and phosphate based on a yield goal of 8.7 m^3/ha. The recommendation is contained in the Colorado State University publication, "Guide to Fertilizer Recommendation in Colorado." A uniform rate of fertilization was maintained over the field.

The corn test plots, Field II, received fertilization such that two levels of nitrogen were achieved in the surface soils. The goal was an equivalent of either 100 ppm nitrogen or 60 ppm nitrogen in the soils. This goal was achieved by: (1) analyzing the surface soils for nutrients; and (2) based on existing nitrate levels, half the plots were selected for fertilization to 60 ppm and the remaining to 100 ppm.

The soil samples used for analysis were taken from adjacent plots and mixed. Soils were mixed for only two plots per analyzed sample. This means that adjacent plots received the same fertilizer treatment; i.e., plot 17 and 18.

By using the approximation (Ludwig and Soltanpour, 1975), that 10 ppm nitrogen is roughly equivalent to 40 kg per hectare of nitrate nitrogen in the top 30 cm of soil, the nitrogen required to achieve a specific nutrient level was computed.

The amount of potassium and phosphate fertilizer required was computed based on recommendations found in the fertilizer guide. The fertilizer was applied on the paired test plots using a fertilizer drill. All fertilizer was carefully weighed

TABLE 1. FERTILIZER ADDED TO FIELD II, 1976

Plot	Rate of Fertilizer Application (kg ha^{-1})		
	NH_4NO_3 (33%)	P_2O_5 (44%)	$ZnSO_4$ (36%)
17	0	132	0
18	0	132	0
19	298	132	0
20	298	132	0
21	488	132	15
22	488	132	15
23	0	78	15
24	0	78	15
25	190	78	0
26	190	78	0
27	0	78	0
28	0	78	0
29	0	132	0
30	0	132	0
31	0	78	0
32	0	78	0
33	0	78	0
34	0	78	0
35	0	78	0
36	0	78	0
37	0	0	0
38	0	0	0
39	0	78	0
40	0	78	0
41	0	78	15
42	0	78	15
43	0	78	0
44	0	78	0
45	0	78	15
46	0	78	15
47	0	0	0
48	0	0	0

to insure proper levels of fertilization. The design of the experiment was dictated by the soil analysis and was random due to this fact.

The plant leaf analysis was carried out by taking 100 leaves from the rows designated for sample harvesting at the time when approximately 75 percent of the field showed silk emergence (5th August). The second leaf down from the top ear was removed for analysis. The leaves were air dried, ground and analyzed for total nitrogen using the semi-micro Kjeldahl method.

Section 6

FIELD OPERATIONS

CULTURAL PRACTICES

Field I was planted to the Resistador variety of alfalfa in the spring of 1974. Before sowing, the field had been fertilized with 44 percent superphosphate (P_2O_5) applied at the rate of 335 kilograms per hectare. No further fertilizer was added prior to or during the course of the study herein described. No weed or insect treatments were found to be necessary.

Field II was planted to corn in the three preceding crop years and again in 1976. The first two years yielded poor crops due to late sowing and the compacting effects of plot construction traffic. Yields from well-watered crops in 1975 were below the Valley average. In 1976, the Pioneer variety 3369A was sown on 29th of April. Both the insecticide Thiamet and the herbicide Lasso were applied prior to sowing. The corn was sown with a four-row planter to give a population of approximately 50,000 plants per hectare.

Following emergence and establishment of the plants, interrow cultivation for weed control was carried out at the beginning of June, followed two weeks later by a surface application of 2,4-D at a rate of 0.6 litres per hectare to control weeds in the rows. A second interrow cultivation was carried out on 20th of June. Those weeds which persisted in the rows designated for sample harvesting were removed by hand hoeing.

In late July, a minor infestation of Western Corn Rootworm and Corn Ear Worm was detected in the crop. Only minor damage occurred before control measures were taken on 30th of July when Parathion was applied from the air at a rate of 0.56 kilograms per hectare.

Field III was planted to the New Gains wheat variety in October 1975. Prior to planting, the field was uniformly fertilized with 44 percent P_2O_5 at a rate of 90 kilograms per hectare of the fertilizer. The wheat was broadcast sown at a rate of 112 kilograms per hectare. The fields were surface-irrigated with furrows spaced at 30-inch (76 cm) centers.

FIELD DATA COLLECTION

The principal activities throughout the crops' growing seasons were the application of water to the crops, monitoring the moisture balance in the root zone, and measuring the amount of fertilizer passing beyond the root zone.

The method of water application was the same for each field. Gated pipe ran across the upper end of each row of plots, as shown in Figure 17. Water measured into the pipe through the V-notch weir (Figure 18) was conveyed to only one plot in the row so that all of the measured water was applied to that plot. Surface runoff from each plot was measured with a 1-inch (25 mm) Cutthroat flume set in the taildrain at the outlet from the plot, as shown in Figure 19. The point of outflow of the subsurface runoff could be measured. No subsurface runoff was noted from any of the plots during the course of the study. A running total of net water application (inflow minus outflow) was recorded on a prepared sheet, with the irrigation halted when the desired depth of water had been applied.

Unfortunately, an error had been made in the original calibration of the V-notch weirs. This error was not discovered until July 14, 1976, when an independent check was made. Until that time, 18 percent less water than intended had been applied per irrigation. At the same time an attempt was made to prevent surface runoff from the plots. The resulting ponding at the ends of the furrows, coupled with the shortage of applied water, caused an unintentional moderate stress to the plants around the middle of the rows during the early stages of the experiment. The effects were more noticeable in some plots than others.

Soil moisture was measured weekly by neutron moisture probe (Figure 20) in the corn plot and by gravimetric means in the wheat plots. The measurements are described in more detail in Section 7.

HARVESTING OPERATIONS

The 32 plots of corn in Field II were partially harvested for forage yield measurements on 17th of September and the remaining unharvested portions of each plot were harvested for grain on the 10th and 11th of November.

Forage yield estimates were made by harvesting two rows on each side of the neutron probe access tubes for a total of four rows per plot, or a total area of 600 square feet (55.7 m^2) per plot. The harvest was accomplished by manually cutting each stalk at ground level, as shown in Figure 21. In order to eliminate any border affects, a 60 foot (18.3 meter) length from

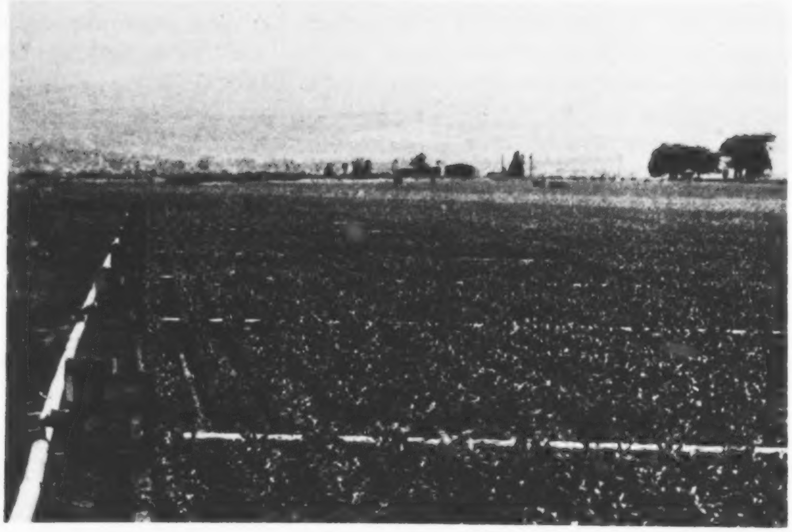


Figure 17. Watering of corn plots using gated pipe.

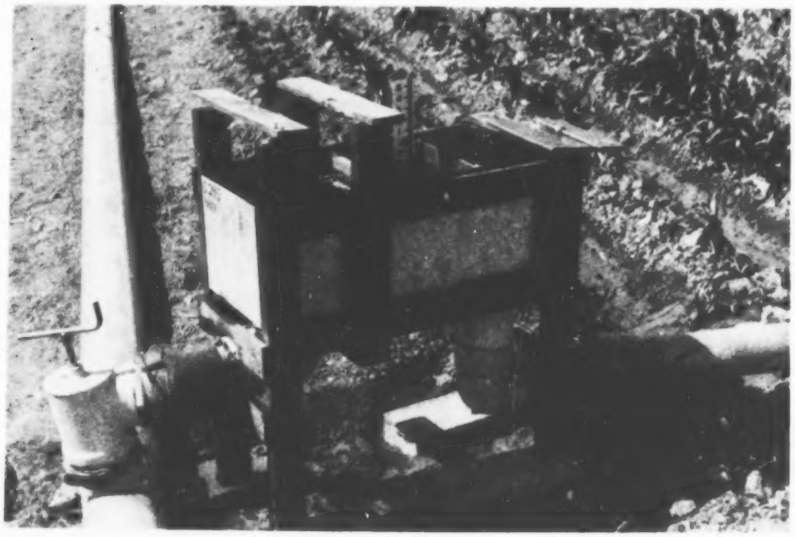


Figure 18. Measurement of water applied to the plots using a V-notch weir.

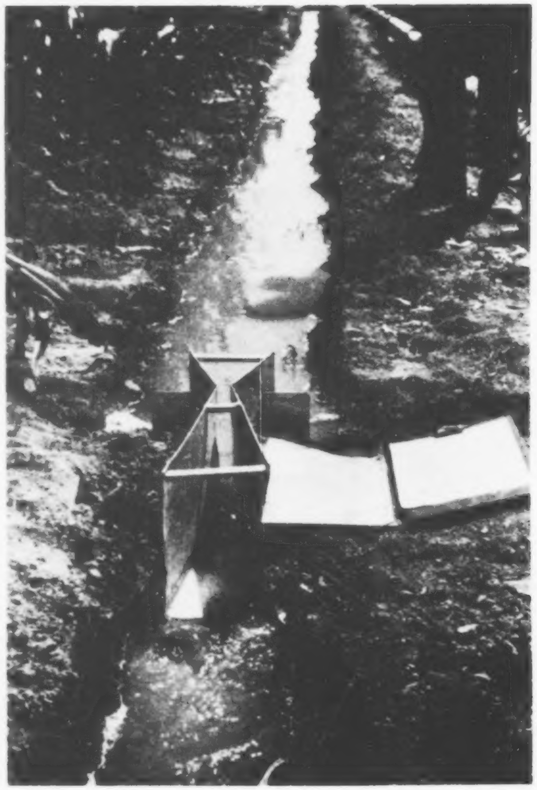


Figure 19. Measurement of surface runoff from the plots using a Cutthroat flume.

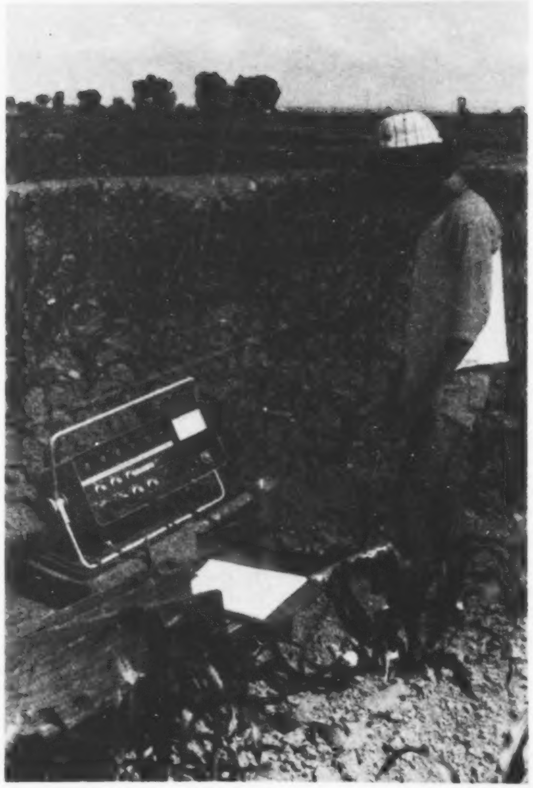


Figure 20. Measurement of soil moisture using a neutron meter.

Figure 21. Harvesting corn for dry matter yield.

Figure 22. Weighing corn samples for dry matter yield.

the center of the rows was harvested and the ends were left standing. A row was also left on each side of the access tube row to exclude plants possibly damaged while taking moisture measurements during the season. The total fresh plant weight from each plot was determined by weighing the sample on a spring tension scale, shown in Figure 22. Four representative plants from each plot were then weighed, air-dried, chopped, weighed, dried on a forced air oven, and reweighed. The dry weight of the harvested material was calculated on the basis of the moisture percentage of the sample. A few of the samples suffered some squirrel damage while being air-dried; however, this was compensated by taking the average weight of the remaining undamaged cobs, multiplying by the number of original cobs and adding this weight to the sample weight.

Grain yield estimates were made by harvesting three rows on each side of the previously harvested forage rows, with the six rows per plot giving a total area of 900 square feet (83.6 m^2) per plot. To eliminate any border effects, a 60 foot (18.3 meter) length from the center of the row was sampled. The harvesting was carried out using the three row "Oliver" combine, shown in Figure 23. The grain was collected in a sack held under the elevator outlet to the combine bin and the weight determined on a spring tension scale. The kernel moisture percentage of each grain sample was determined using a "Motomco" moisture meter. The grain weight per sample area was converted to kilograms per hectare at 15.5 percent moisture.

Field III contained 10 wheat plots of variable dimensions; consequently, the harvested area varied according to the width and length of each plot. The wheat was harvested on 27th of July using the "Hege 125" experimental plot combine shown in Figure 24, which has a 4-foot (1.2 meter) wide cutting head. For the plots measuring 100 feet x 100 feet, two swaths were cut through the plot, each being 20 feet (6.1 meters) from the sides of the plot. For the plots measuring 40 feet x 200 feet and 40 feet x 300 feet, only one swath was cut through the plots, this being located near the center of the plots. The grain was collected in sacks and later weighed on a spring tension scale. Grain bushel weight was also determined for each sack of grain and averaged for each plot. The dimensions of each cut was measured and the sampling area calculated for each plot. This was used to give a yield estimation for each plot in kilograms of grain per hectare.

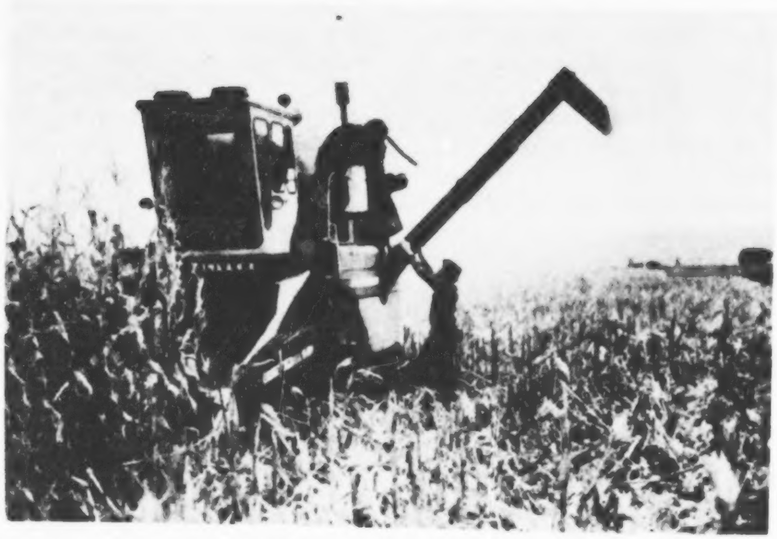


Figure 23. Combine used for harvesting corn grain samples.

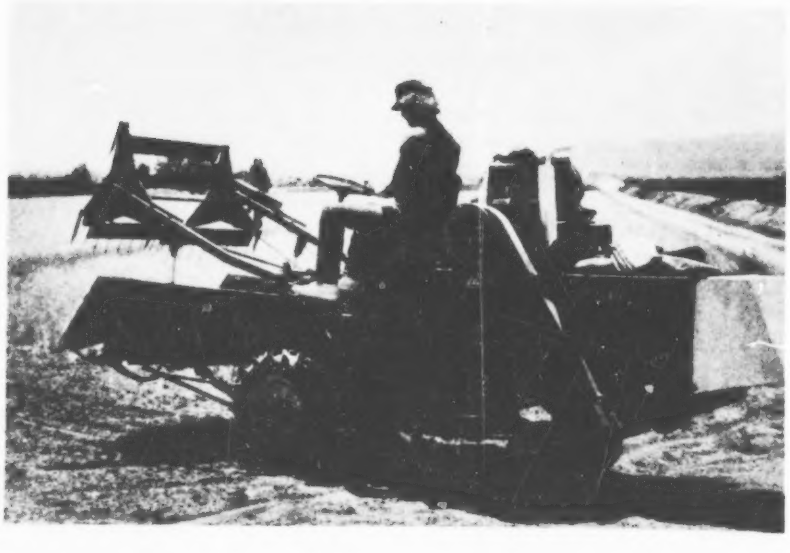


Figure 24. Combine used for harvesting wheat samples.

Section 7

EVAPOTRANSPIRATION

DATA COLLECTION

Climatic data were collected in the southern part of Field III on Matchett Farm. The weather station was located in a field sown to José Tall Wheatgrass. Readings were taken every morning, including weekends, at approximately 8 a.m. The daily data obtained are listed in Appendix A for the period from April 1, to November 9, 1976.

Maximum and minimum temperatures were recorded on a hygrothermograph as well as on a maximum and minimum thermometer. The thermometer readings were used in the ET_p estimates as it was felt that these are inherently more accurate.

Rainfall was constantly monitored with a tipping bucket rain gauge, with the registrations recorded on a strip chart. The tipping bucket was activated by each 0.01 inch (0.254 mm) of rainfall.

Relative humidity was continuously recorded on the hygrothermograph. The recorded value is that which occurred at the time of minimum temperature, and generally corresponds to the maximum value for the day.

Solar radiation values were read from the solar radiometer located in the weather station. The value read from the integrator in the morning of a particular day was subtracted from the value read in the morning of the subsequent day, with the counts multiplied by the calibration factor of 0.200 to give the value of measured solar radiation for that day (R_s) in langleys (calories cm^{-2}) per day.

During the early part of the season the solar radiometer was out of order and values of R_s were obtained from the Agricultural Research Service (ARS) weather station located in the valley. These values were obtained for a period of 54 days after the solar radiometer was repaired on the 11th of May so that a correlation between the ARS values and the CSU values could be obtained. The overlapping data was matched best by a power curve fit:

$$(R_s)_{CSU} = 1.569(R_s)_{ARS}^{0.915} \quad (r^2 = 0.916) \; . \; . \; . \; . \; .(26)$$

and this function was used to fill in the missing R_s data at Matchett Farm during late April and early May.

Wind run was measured with an anemometer located 2 meters above the ground. Over the period 7th of August to 20th of September the anemometer was broken and wind run data was obtained from the Weather Bureau station located at Walker Field approximately 2 kilometers to the northwest. Measurements at this location are made 6.7 meters above the ground. Windspeed at an elevation of 2 meters can be approximated from measurements made at other elevations using the power law:

$$W_2 = W_z(2/z)^{0.2} \quad \text{(Pair et al., 1969, p. 105)} \; . \; .(27)$$

where z is the elevation in meters at which W_z is measured. Using this relationship,

$$(W_2)_{CSU} = (W_{6.7})_{WF}\left(\frac{2}{6.7}\right)^{0.2} = 0.785(W_{6.7})_{WF} \quad . \; . \; .(28)$$

data from Walker Field, $(W_{6.7})_{WF}$, were collected for July through October and plotted against the available CSU records for the same period. A better fit to the data was actually obtained using:

$$(W_2)_{CSU} = 0.833(W_{6.7})_{WF} \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; .(29)$$

and this relationship was used to fill in the missing data.

Evaporation was measured in a U.S. Class A pan set on a platform with the pan rim 45 centimeters above the ground. The surrounding field was planted to Jose Tall Wheatgrass for a distance of approximately 125 meters in the direction of the prevailing wind. The values of evaporation given in Appendix A are direct readings from the pan and, hence, rainfall amounts must be added to give the net value of evaporation for the day. Consequently, some readings on days in which rainfall occurred are negative.

Two volumetric lysimeters, one meter square and 0.5 meters deep, were planted to subterranean clover and set level with the ground surface. Each lysimeter was supplied water from a tank approximately 1.5 meters high and 32 centimeters in diameter, with the level of the water in the lysimeter maintained approximately 10 centimeters below the soil surface by a float valve.

The lysimeters began to give unrealistically high values of ET_p in early June. In July, one lysimeter was excavated and inspected for leaks. No leaks were found and the lysimeter was returned to the ground. At the same time the subterranean clover overhanging the sides of both lysimeters was trimmed. Although this overhang did not appear significant at first, on measurement it was found to have increased the transpiring surface area by approximately 65 percent. After cutting, ET values reduced significantly, although an instantaneous reduction was not apparent (see Figure 25).

Soil moisture in the corn crop was measured weekly by neutron moisture probe at 30 cm intervals to a depth generally in excess of 180 cm, or to shale, whichever occurred first. Two access tubes were placed in the bed of the center row of each plot, 25 feet (7.6 meters) apart and equidistant from each end of the plot. Moisture in the top 15 cm of soil was measured gravimetrically. Because neutron probe access tubes could not be installed without damage to the growing crop, soil moisture measurements in the wheat crop were made gravimetrically each week to a depth of 120 cm or to shale, whichever came first. By integrating the moisture measurements over the depth of measurement, changes in root-zone soil moisture storage from week to week could be calculated.

COMPARISON OF METHODS OF ET CALCULATION

A comparison of the computed and measured values of ET_p, for the 27 week period of consideration during the summer of 1976, is given in Table 2 and is plotted in Figure 25. The ET_p values computed by the Penman method and the Jensen-Haise method, calibrated for local conditions, were in very close agreement. Over the 27-week period, the ET_p computed by the Penman method was 1309 millimeters, or 2.8 percent higher than the 1273 millimeters computed by the Jensen-Haise method. The percentage difference on a week-by-week basis was usually higher, although for two-thirds of the time the weekly values of ET_p computed by the two methods were within 10 percent of each other. The biggest difference was 22 percent.

Errors in ET_p estimates using weekly time periods are to be expected. Jensen and Wright (1976) found an estimated standard error of 1.0 millimeters per day at Kimberly, Idaho, using daily data, with this error decreasing inversely with the square root of the number of days for time periods up to 30 days. Therefore, the variation in estimates of weekly ET_p using the Penman or Jensen-Haise method is to be expected.

Pan evaporation over the first 24 weeks (after which water in the pan was frozen) was 90 percent of ET_p calculated by the Penman method. The discrepancy was much less over the first 12

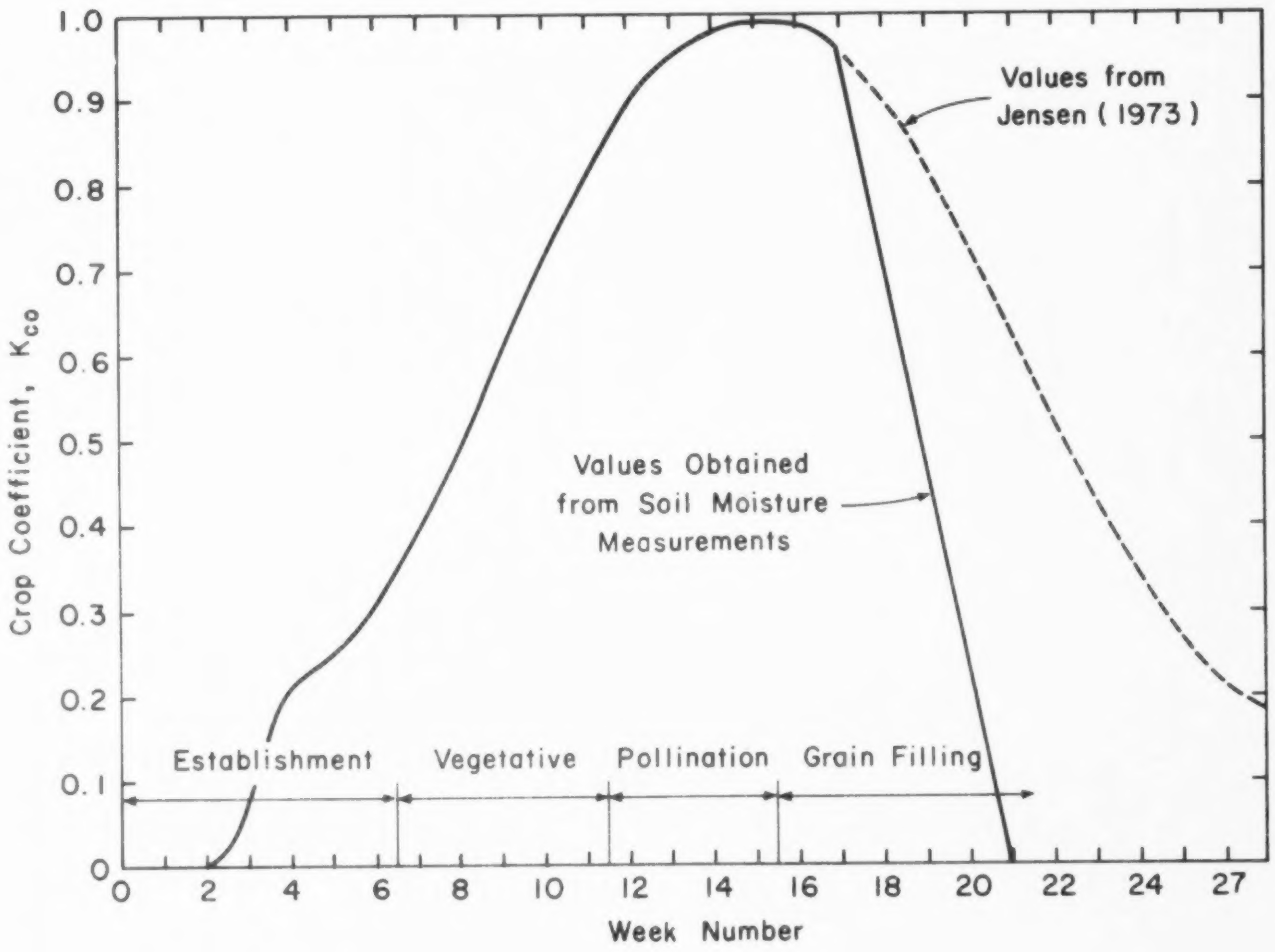


Figure 25. Variation of crop coefficient with time.

TABLE 2. COMPARISON OF POTENTIAL EVAPOTRANSPIRATION ESTIMATES AND EVAPORATION DATA

Week	Modified Julian Date	Interval	Estimated Potential Evapotranspiration, mm per week						Evaporation (including rainfall) mm per week
			Penman	Jensen-Haise	Lysimeter Use			USBR Penman	
					North	South	Average		
1	64-70	May 3-9	29.5	29.5	31.5	19.7	25.6	27.6	18.6
2	71-77	10-16	56.7	52.4	27.2	25.6	26.4	38.9	50.3
3	78-84	17-23	33.9	36.5	32.2	27.8	30.0	28.7	42.1
4	85-91	24-30	46.9	46.7	52.9	39.8	46.4	37.1	43.1
5	92-98	May 31-June 6	66.4	61.2	86.3	71.2	78.8	50.9	56.4
6	99-105	June 7-12	68.9	54.0	106.8	87.3	97.1	54.3	65.6
7	106-112	14-20	63.3	58.1	120.3	104.4	112.4	39.8	65.2
8	113-119	21-27	58.3	60.5	124.9	107.1	116.0	44.7	67.8
9	120-126	June 28-July 4	70.6	71.9	148.2	128.0	138.1	52.6	66.3
10	127-133	July 5-11	76.2	76.3	136.1	117.1	126.6	56.5	64.6
11	134-140	12-18	61.4	66.0	112.2	82.7	97.5	49.5	63.7
12	141-147	19-25	57.7	65.6	87.7	74.3	81.0	47.2	60.4
13	148-154	July 26-Aug. 1	55.2	61.5	58.6	54.4	56.5	45.3	48.6
14	155-161	Aug. 2-8	63.2	52.5	61.2	51.4	56.3	47.3	49.7
15	162-168	9-15	59.0	55.9	45.8	45.4	45.6	47.0	51.6
16	169-175	16-22	53.6	55.3	58.9	43.3	51.1	42.9	44.0
17	176-182	23-29	54.3	58.7	64.3	50.2	57.3	44.6	52.3
18	183-189	Aug. 30-Sept.5	60.0	57.9	62.2	47.5	54.9	44.4	51.1
19	190-196	Sept. 6-12	30.7	37.6	32.0	31.6	31.8	27.8	27.0
20	197-203	13-19	45.6	43.3	47.0	37.1	42.0	34.5	38.6
21	204-210	20-26	26.8	27.5	43.7	17.8	30.8	26.2	18.4
22	211-217	Sept. 27-Oct.3	33.1	30.4	43.4	25.2	34.3	25.8	21.9
23	218-224	Oct. 4-10	31.1	28.7	19.3	10.0	14.7		22.9
24	225-231	11-17	33.8	28.1	19.7	15.0	17.4		24.4
25	232-238	18-24	26.6	19.3					
26	239-245	25-31	22.5	17.1					
27	246-252	Nov. 1-7	23.6	20.2					
		TOTAL	1309	1273					1115

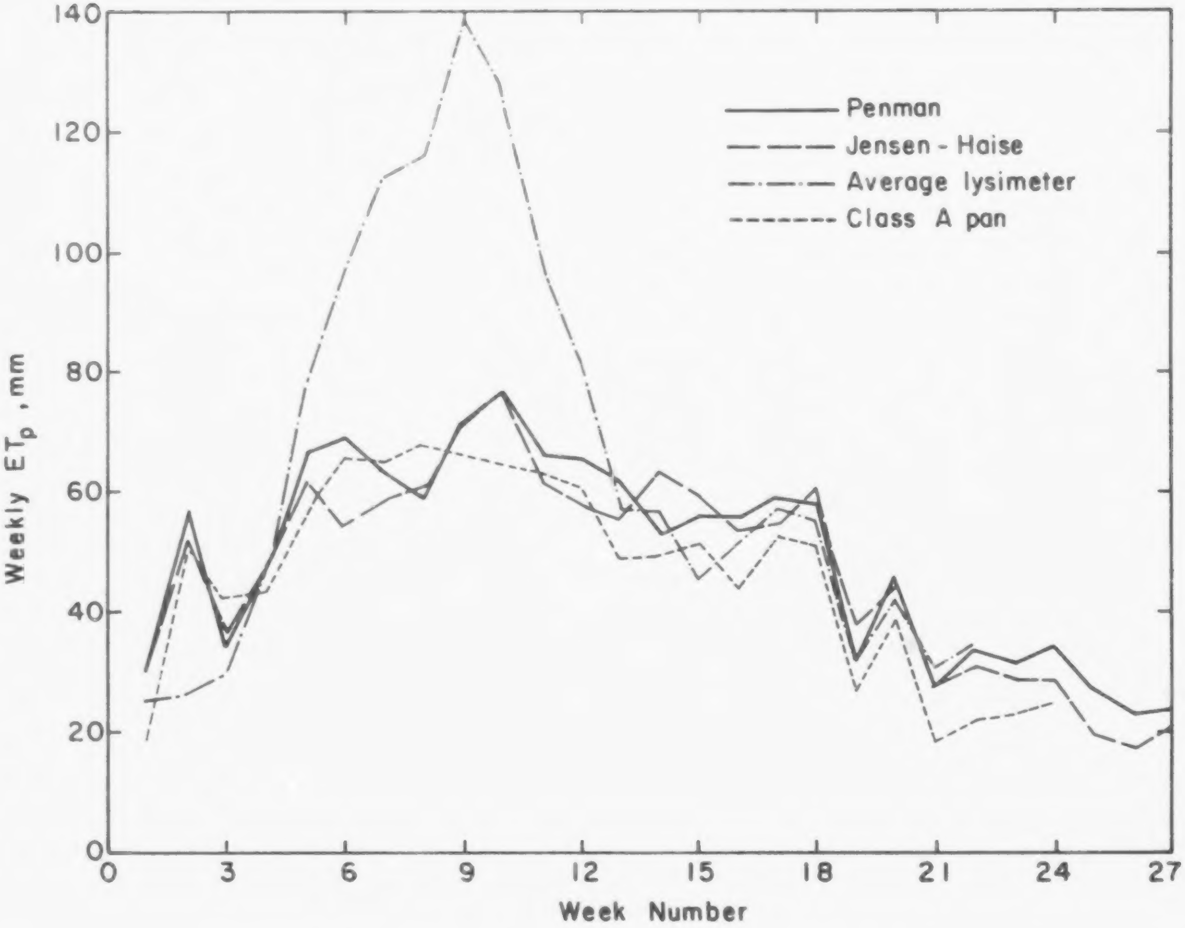


Figure 26. Computed and measured water use.

weeks. Hanks and others at Logan, Utah, found uncorrected pan evaporation a good measure of ET_p (Consortium for International Development, 1976).

Although the uncorrected pan evaporation results are in good agreement with the values of ET_p calculated, a pan factor correction would normally be expected. Published values indicate a pan factor of 0.7 for the given conditions (Doorenbos and Pruitt, 1975, Table 19). Using this factor, the calculated value of seasonal ET would be:

$$ET = 0.7 \times 1115 \times \frac{650}{1236} \quad \ldots\ldots\ldots\ldots\ldots \quad (30)$$

$$= 410 \text{ mm}$$

where 1115 is the evaporation (including rainfall) in millimeters up until the time the water in the pan froze, and 650/1236 is a representation of the seasonal crop factor (ET/ET_p by Penman's method). This value of ET is well below that which would be reasonably expected and indicates the necessity of locally calibrated values of the pan factor in using pan evaporation as a measure of ET_p.

The good agreement between the three methods discussed above would indicate that ET_p may be estimated on a seasonal basis with a reasonable degree of reliability using any of the methods provided they are locally calibrated. The closer agreement between the Penman and Jensen-Haise methods, compared to pan evaporation, would point in their favor, but without accurate lysimeter measurements, a definite conclusion cannot be drawn.

The lysimeter data are obviously in error during the first half of the season, as discussed earlier. Average lysimeter values of the remainder of the season are in quite good agreement with the computed values, but the discrepancies between the readings from the two lysimeters in many cases makes an average reading of dubious value.

The values of ET_p calculated from the USBR data would appear unduly low. The peak value following tasseling of 47.3 millimeters per week corresponds to an average of 6.8 millimeters per day which would appear too low for fully grown corn.

Weekly estimates of ET_p using combination equations cannot be expected to have great accuracy, as discussed above. Estimates by the Penman method were used for the weekly ET computations for the corn, as the Penman equation incorporates more of the factors influencing evapotranspiration.

CROP WATER USE

Consumptive use of water by a well-watered crop may be most accurately obtained by growing the crop in a lysimeter in the field. Such an arrangement was not possible in this experiment, where volumetric lysimeters sown to subterranean clover were located adjacent to the experimental plots. As described earlier, the lysimeters were found to be malfunctioning during the course of the experiment and hence evapotranspiration of the well-watered plots was computed using Penman's combination equation. Evapotranspiration was calculated on a weekly basis as the crops were watered on a weekly schedule.

For the corn crop grown in Field II, the calculated values of potential evapotranspiration were multiplied by a crop coefficient (K_{CO}) to obtain crop evapotranspiration. The crop coefficients used are those presented by Jensen (1973). Using the coefficients presented, the calculated seasonal ET was excessively high (840 mm). Doorenbos and Pruitt (1975) consider the maximum crop evapotranspiration for corn grown under arid conditions to be 700 mm. Therefore, two adjustments were made to the crop coefficients:

1. As the crop was "watered up" after planting, the crop coefficient was taken as zero in the two weeks preceding emergence, rather than having values ascribed from the week of planting.

2. A check of the soil moisture measurement data showed that, by Week 21 (22nd September), moisture extraction from the root zone had ceased. A straight line was therefore drawn on the crop coefficient curve from the value at Week 17 (23rd August) to zero at Week 21. This closely accords with the values of Doorenbos and Pruitt (1975). The effect of this adjustment on the weekly crop coefficients as given by Jensen (1973) is shown in Figure 26.

The tabulation of the weekly crop coefficients and computation of the maximum crop evapotranspiration is given in Table 3. The parameters used in calculating potential ET by the modified Penman method are given in Appendix B. Effective cover was assumed to occur ten days after the well watered plots reached about 50 percent tasseling. Therefore, the date of effective cover was 31st of July which was 93 days after planting and 75 days after emergence.

Moisture measurements were made weekly using the neutron probe, in most cases to a depth exceeding 180 cm, or to the underlying shale. The water balance (applied water + rainfall + change in soil moisture storage) was summed for each of the growth stages shown in Figure 26. The water balance generally exceeded the crop evapotranspiration computed as described above,

TABLE 3. COMPUTATION OF ET FOR WELL-WATERED CORN CROP

Week	Date	K_{co}	Penman ET_p (mm)	ET (mm)
1	May 3-9	0	29.5	0
2	10-16	0	56.7	0
3	17-23	0.08	33.9	3
4	24-30	0.21	46.9	10
5	May 31-June 6	0.25	66.4	17
6	June 7-13	0.31	68.9	21
7	14-20	0.40	63.3	25
8	21-27	0.49	58.3	29
9	June 28-July 4	0.61	70.6	43
10	July 5-11	0.71	76.2	54
11	12-18	0.81	61.4	50
12	19-25	0.90	57.7	52
13	July 26-Aug. 1	0.95	55.2	52
14	Aug. 2-8	0.98	63.2	62
15	9-15	0.99	59.0	58
16	16-22	0.99	53.6	53
17	23-29	0.95	54.3	52
18	Aug. 30-Sept. 5	0.72	60.0	43
19	Sept. 6-12	0.48	30.7	15
20	13-19	0.25	45.6	11
21	20-26	0	26.8	0
22	Sept. 27-Oct. 3	0	33.1	0
23	Oct. 4-10	0	31.1	0
24	11-17	0	33.8	0
25	18-24	0	26.6	0
26	25-31	0	22.5	0
27	Nov. 1-7	0	23.6	0
			TOTAL	650

indicating that some water was lost to drainage. There was not sufficient drainage that it could be measured as outflow from the plots. In those cases where the water balance for a particular growth stage was less than the computed crop evapotranspiration, this lower value was used for crop ET.

Evapotranspiration from plots not receiving water was obtained by measuring the soil moisture in the crop root zone each week with the neutron probe. In these plots, no drainage was taking place, allowing ET to be obtained by taking the difference in soil moisture between successive weeks, plus rainfall. Rainfall was extremely light during the growing season and hence was taken as fully effective. The ET derived for each growth stage is shown in Appendix C.

Because of the late start in data collection, the crop water use computations for the wheat must be considered less accurate. As soil moisture data were not collected until mid-May, the ET for the preceding period was taken as the difference between the moisture content at field capacity and the moisture content at the time of first measurement, plus the intervening precipitation. The intervening precipitation, totaling 102 mm, was well distributed (the maximum daily total was 15 mm, with no other daily amounts over 6 mm) and hence was taken as fully effective. For the remainder of the season, the crop ET was computed or measured in the same manner as for the corn crop, using the appropriate crop coefficient from Jensen (1973), also truncated at the end of the season. The data are listed in Appendix F.

SECTION 8

CROP YIELDS AND WATER USE

CORN

The variation of grain yield and dry matter yield with evapotranspiration has been plotted in Figures 27 and 28, respectively. A positive correlation between yield and ET exists in both cases, with the data exhibiting a scatter similar to that found by other researchers such as Stewart, et al. (1975) and the Consortium for International Development (1976). The numerical results from each plot are given in Appendix D.

As discussed earlier, scatter in the production relations can be expected due to growth stage effects, particularly in relation to grain yields. In the experiment conducted here, the scatter was possibly exaggerated by variations in soil characteristics from plot to plot. The soil texture and structure showed slight variations throughout the field, but the major physical difference was the variation in depth. In addition, the soil exhibited differences in salinity level and some difference in fertility. Insect and rodent problems may also have had some adverse effects on the results.

Soil Fertility Affect on Yield

Fertilization of all fields for the 1976 season was based on recommendations by the CSU Soil Testing Laboratory, Fort Collins, Colorado. Composite soil samples from pairs of plots were made to a depth of 30 cm. These samples were analyzed and fertilizer recommendations made for a projected 150 bu per acre (7476 kg per ha) yield of grain. Pairs of plots were broadcast fertilized independently, in order to bring the field to a constant or normalized level of fertility (Table 1).

Knowing that soil fertility differences may give erroneous yield results in the interpretation of the irrigation data, it was important to investigate any fertility differences that existed within the field. The irrigation treatments placed varying degrees of stress on the crop's ability to mine nutrients from the soil. Plant analysis was used to indicate the fertility status of the soil.

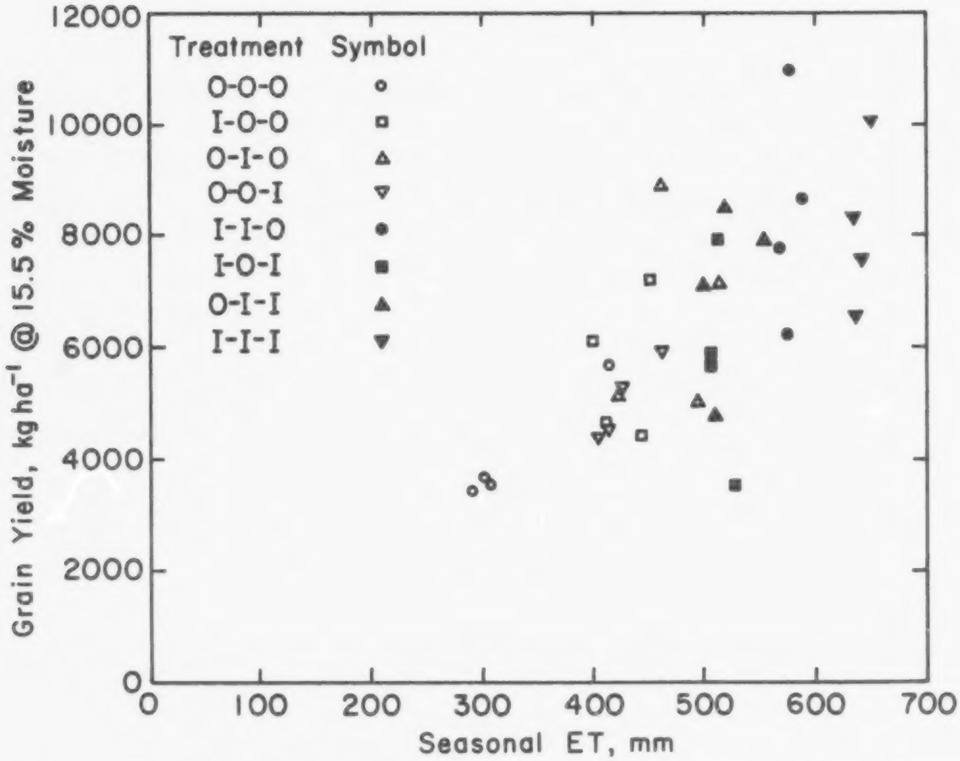


Figure 27. Variation of grain yield of corn with seasonal evapotranspiration.

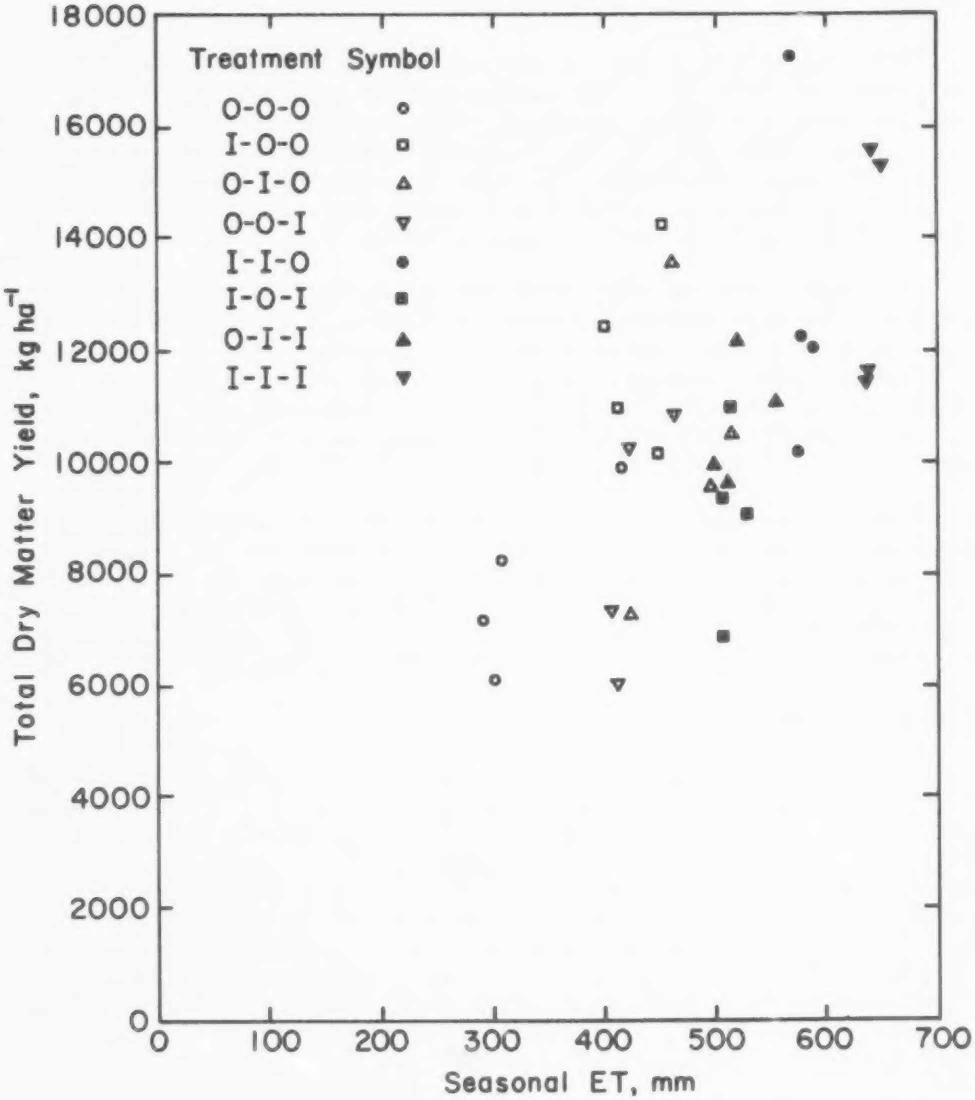


Figure 28. Variation of dry matter yield of corn with seasonal evapotranspiration.

Research has shown that plant leaf analysis is a reasonably accurate method of evaluating differences in fertility status of the soil. The soil test data (Table 4) and the fertilization practices (Table 1) indicate that P, K, Fe and Zn should not be limiting to the crop. It was expected that N was the major element influencing corn yields and was used as the indicator element in the plant leaf analysis.

When approximately 75 percent of the field showed silk emergence (August 5), 100 leaf samples of the second leaf down from the top ear were obtained from the harvest rows of each plot. They were air dried, ground and analyzed for the determination of total N content in the laboratory. The semi-micro Kjeldahl method for total N was used for the analysis (Black, 1965). The results are shown in Table 5.

The analysis of variance revealed no significant difference in leaf tissue N content among irrigation treatments on August 5. Thus, it was first assumed that no significant soil fertility differences were present among irrigation treatments. There was, however, a high correlation (r=0.87) between the percentage N in the leaf tissue and yield of the various irrigation treatments when the 0-0-0 treatment was excluded (Figure 29).

The percentage of N in corn leaves at near maximum yield is reported to be between 2.5 and 3.0 (Pierre et al., 1966). Maximum yields in this experiment were in excess of the projected grain yields for which the fertilizer recommendations were based. It is therefore possible that higher yields could have occurred had a higher N fertilization rate been applied (Treat, 1978).

Salinity Effects on Yield

A high salt content in the soil adversely affects the plant's ability to absorb water and nutrients vital to its development. This becomes especially critical when attempting to study the effects of moisture stress on yield. High salt concentrations impose a far greater amount of moisture stress on the plant than normally would be imposed in a nonsaline soil. It was suspected that if saline areas were present in the field they could influence the yield results of the irrigation treatments. Therefore, in order to determine if high salt concentrations existed in the field, salinity measurements were obtained on each plot.

Soil samples were collected to a depth of 4 feet (120 cm) in mid-July using a soil "King" tube. A composite sample was taken consisting of two cores from the middle harvest row on each side of the two neutron probe access tubes, giving a total of four cores from each plot. An analysis of the electrical conductivity (EC) of the soil saturated extract and the pH of a saturated soil paste was made in the laboratory. The results are shown in Table 6.

TABLE 4. SOIL ANALYSIS FROM WHICH FERTILIZER RECOMMENDATIONS WERE BASED

PAIRED PLOTS	pH	SALTS mmhos/cm	%ORGANIC MATTER	NO_3-N ppm	P ppm	K ppm	Zn ppm	Fe ppm
17-18	7.6	7.0	0.9	+99	13	165	1.1	8.1
19-20	7.7	4.7	0.9	36	14	154	1.1	7.4
21-22	7.6	2.4	0.8	21	9	128	0.9	9.3
23-24	7.6	4.7	1.0	+99	16	160	1.0	7.8
25-26	7.7	3.0	0.8	39	15	148	1.1	8.3
27-28	7.8	4.5	0.9	61	18	183	1.1	7.1
29-30	7.6	3.4	0.9	73	13	200	1.1	8.5
31-32	7.6	4.2	0.8	+99	15	175	1.1	7.5
33-34	7.7	3.8	1.0	+99	17	158	1.2	12.9
35-36	7.5	4.0	1.0	70	15	183	1.1	8.1
37-38	7.6	5.2	0.9	+99	19	195	1.4	7.3
39-40	7.4	4.5	0.9	+99	18	220	1.1	8.9
41-42	7.7	3.7	1.1	78	20	250	1.0	7.6
43-44	7.6	3.4	0.9	+99	20	225	1.2	12.9
45-46	7.5	5.5	1.0	+99	18	195	1.0	6.0
47-48	7.6	4.5	1.2	+99	27	278	1.4	17.0
MEAN	7.6	4.3	0.9		17	189	1.1	9.0
S.DEV.	0.09	1.08	0.11	26.90	4.01	39.46	0.13	2.84

TABLE 5. ANALYSIS OF VARIANCE OF PERCENT TOTAL NITROGEN IN CORN LEAVES

Irrigation Treatment	Rep I	Rep II	Rep III	Rep IV	Mean
I-0-I	1.66	1.46	2.02	1.55	1.67
0-I-0	1.87	1.82	2.09	1.46	1.81
0-0-0	1.94	2.06	1.83	2.06	1.97
0-0-I	1.69	1.43	1.67	1.13	1.48
I-I-I	2.17	1.71	2.23	2.05	2.04
I-I-0	2.05	2.12	2.06	2.18	2.10
I-0-0	1.82	1.24	2.15	2.41	1.91
0-I-I	1.62	2.32	2.11	1.86	1.98
Mean	1.85	1.77	2.02	1.84	1.87

Source	df	SS	MS	F
Total	31	3.052		
Replication	3	1.274	0.091	1.21 NS
Treatment	7	1.207	1.172	2.29 NS
Error	21	1.571	0.075	

Std. Dev. = 0.27

C.V. = 14.44%

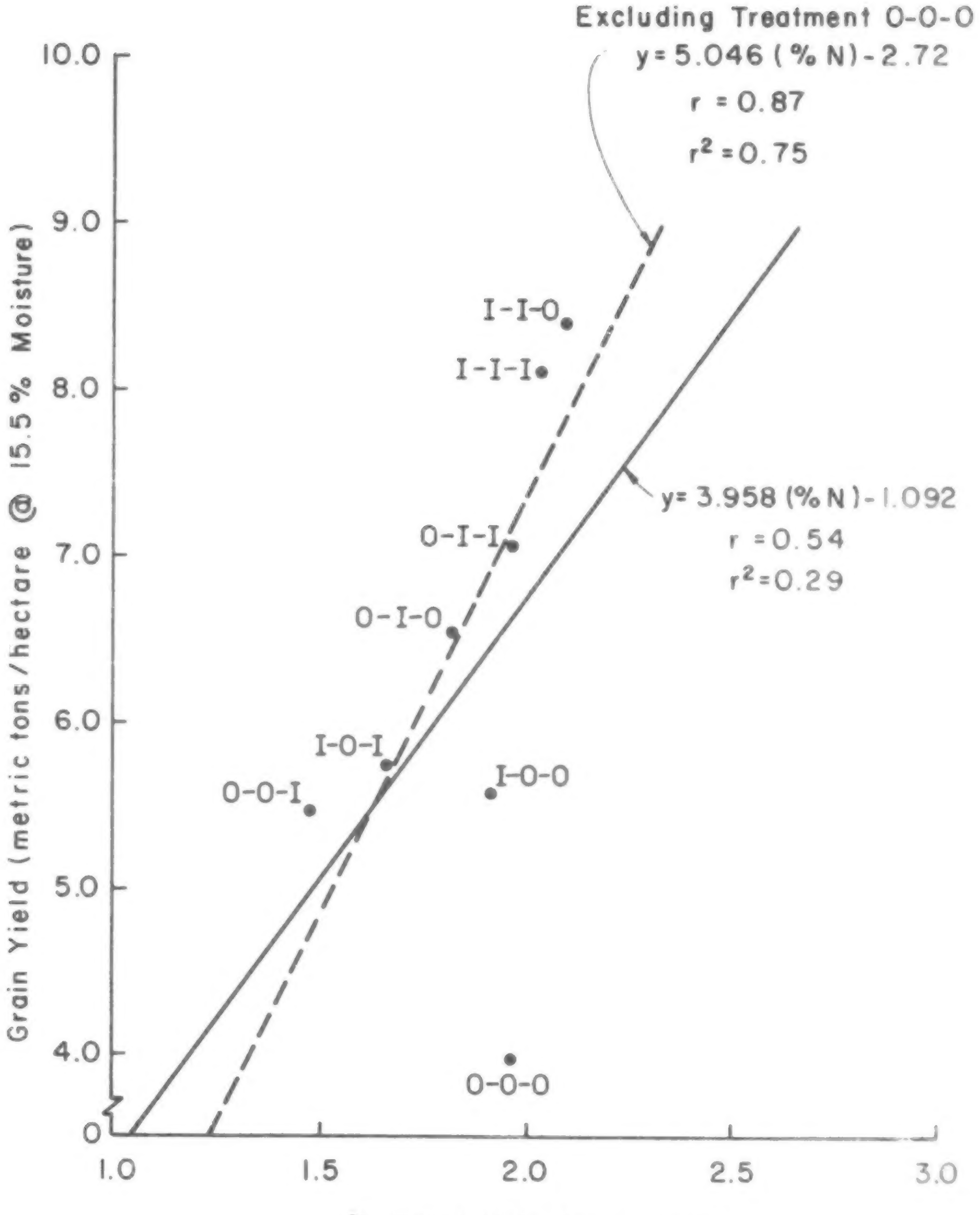


Figure 29. Grain yield in relation to the percent nitrogen in the corn leaves.

TABLE 6. pH AND THE ELECTRICAL CONDUCTIVITY OF COMPOSITE SOIL SAMPLES FROM EXPERIMENTAL PLOTS*

	Plot	pH	EC (mmhos./cm at 25° C)
Rep I	17	7.4	5.37
	18	7.1	3.62
	19	7.2	4.07
	20	7.2	2.63
	21	6.9	3.53
	22	7.5	2.17
	23	7.4	3.58
	24	6.9	3.88
Rep II	25	7.5	3.62
	26	7.1	4.43
	27	7.0	1.99
	28	6.7	3.66
	29	7.1	1.70
	30	7.4	1.98
	31	7.3	1.63
	32	6.9	3.68
Rep III	33	7.4	1.80
	34	7.4	4.13
	35	7.4	2.13
	36	7.5	3.59
	37	6.6	3.58
	38	7.3	2.07
	39	7.5	2.88
	40	7.3	3.37
Rep IV	41	7.2	3.19
	42	6.9	1.92
	43	7.8	1.55
	44	7.2	2.81
	45	7.3	3.24
	46	6.9	3.32
	47	7.4	3.58
	48	7.4	3.41

*pH of saturated paste, conductivity of saturation extract

The average electrical conductivity for all plots was 3.1 mmhos cm^{-1}, and ranged from 1.5 mmhos cm^{-1} to 5.4 mmhos cm^{-1}. The pH values averaged 7.22, and ranged from 6.6 to 7.8. The sodium adsorption ratio of samples collected during the previous winter was about 2.

The electrical conductivity of the soil saturated extract indicates that salinity could have had a small influence on corn yields. Bernstein (1964) reports that a small yield decrement can be expected for corn when EC values exceed 3.3 mmhos cm^{-1} and that a 10 percent yield decrement is possible for values exceeding 5.0 mmhos cm^{-1}. Yields probably were only slightly affected in this experiment since the two plots with the highest salinity (17 and 26) were not stressed during the season (Treatment I-I-I). A statistical analysis of the electrical conductivity values shows no significant difference for either soluble salt content among replication or for irrigation treatments (Table 7). It is possible, however, that salinity may have caused a yield difference between treatments I-I-0 (3.07 mmhos cm^{-1}) and I-I-I (3.86 mmhos cm^{-1}) due to the higher EC values for treatment I-I-I. All pH values were found to be in a range favorable for plant development (Treat, 1978).

Basis for Yield Analysis

An aerial view of the corn plots (Figure 30) shows the variation in development of the crop under the different moisture regimes. The difference between two of the plots is shown in Figure 31.

To reduce the impact of any of these yield-reducing factors described above, apart from ET, on yield, averages were taken of yield and ET values for the plots making up a given treatment. This allows easy assessment of the relative water use efficiencies of the different irrigation treatments, as shown in Figure 32 and 33 for grain yield and dry matter yield, respectively.

The linear upper bound on the grain yield has been plotted on Figure 32. This represents the maximum yield for a given quantity of ET with the water applied under the regimes tested here. Three constraints were imposed in plotting the line: (a) it should pass through the point having the highest water use efficiency; (b) a positive amount of ET is required to produce any grain, i.e., its projection should cut the abscissa to the right of the origin; and (c) it should pass through the data point corresponding to the 0-0-0 treatment.

The last point is not altogether readily justifiable, although it is based on the results of other researchers. For example, from their work with pinto beans, Stewart, et al. (1976) believe that the yield reduction in Treatment 0-0-0 is primary, with no secondary yield losses from nonoptimal timing of deficits.

TABLE 7. AN ANALYSIS OF VARIANCE OF THE ELECTRICAL CONDUCTIVITY FOR COMPOSITE SOIL SAMPLES TAKEN FROM THE VARIOUS IRRIGATION TREATMENTS (ALL VALUES IN mmhos cm^{-1} at 25°C)

Irrigation Treatment	Rep I	Rep II	Rep III	Rep IV	Mean
0-0-0	2.63	3.68	3.59	3.24	3.29
0-0-I	2.17	3.62	2.13	3.19	2.78
I-0-I	4.07	1.70	4.13	3.20	3.28
0-I-0	3.62	3.66	3.58	1.92	3.20
0-I-I	3.58	1.63	1.80	2.81	2.46
I-0-0	3.88	1.99	2.88	1.55	2.58
I-I-0	3.53	1.98	3.37	3.41	3.07
I-I-I	5.37	4.43	2.07	3.58	3.86
Mean	3.60	2.84	2.94	2.86	3.07

AOV TABLE

Source	df	SS	MS	F
Total	31	27.31		
Replication	3	3.21	1.07	1.23 NS
Treatment	7	5.76	0.82	0.94 NS
Error	21	18.34	0.87	

Std. Dev. = 0.93

C.V. + 30.40%

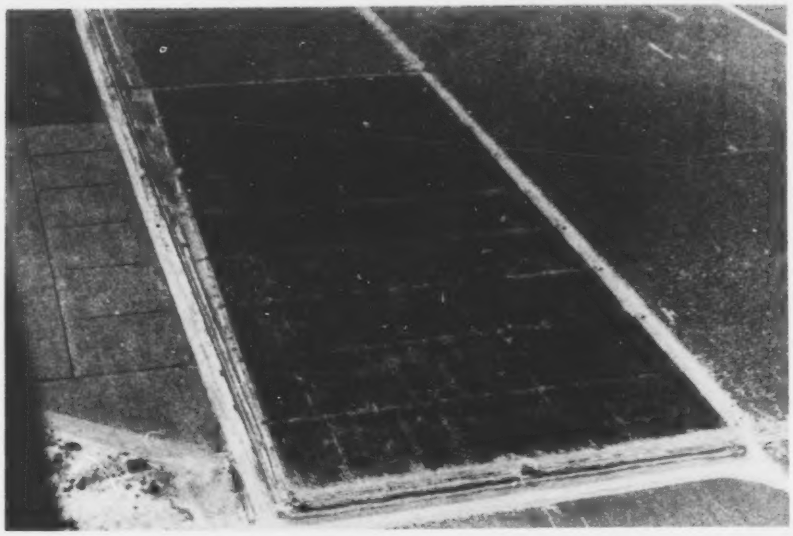


Figure 30. Variation in corn crop resulting from different irrigation regimes (view to the south).

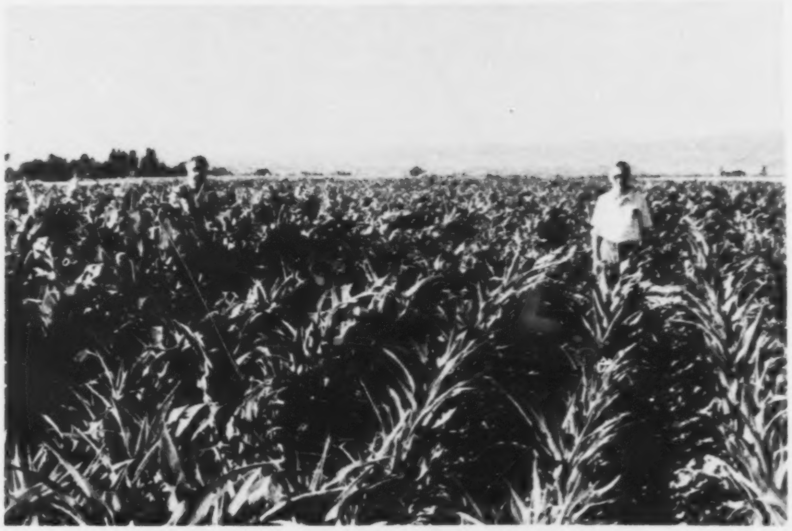


Figure 31. Difference in plant development between well-watered corn plot (left) and stressed plot (right).

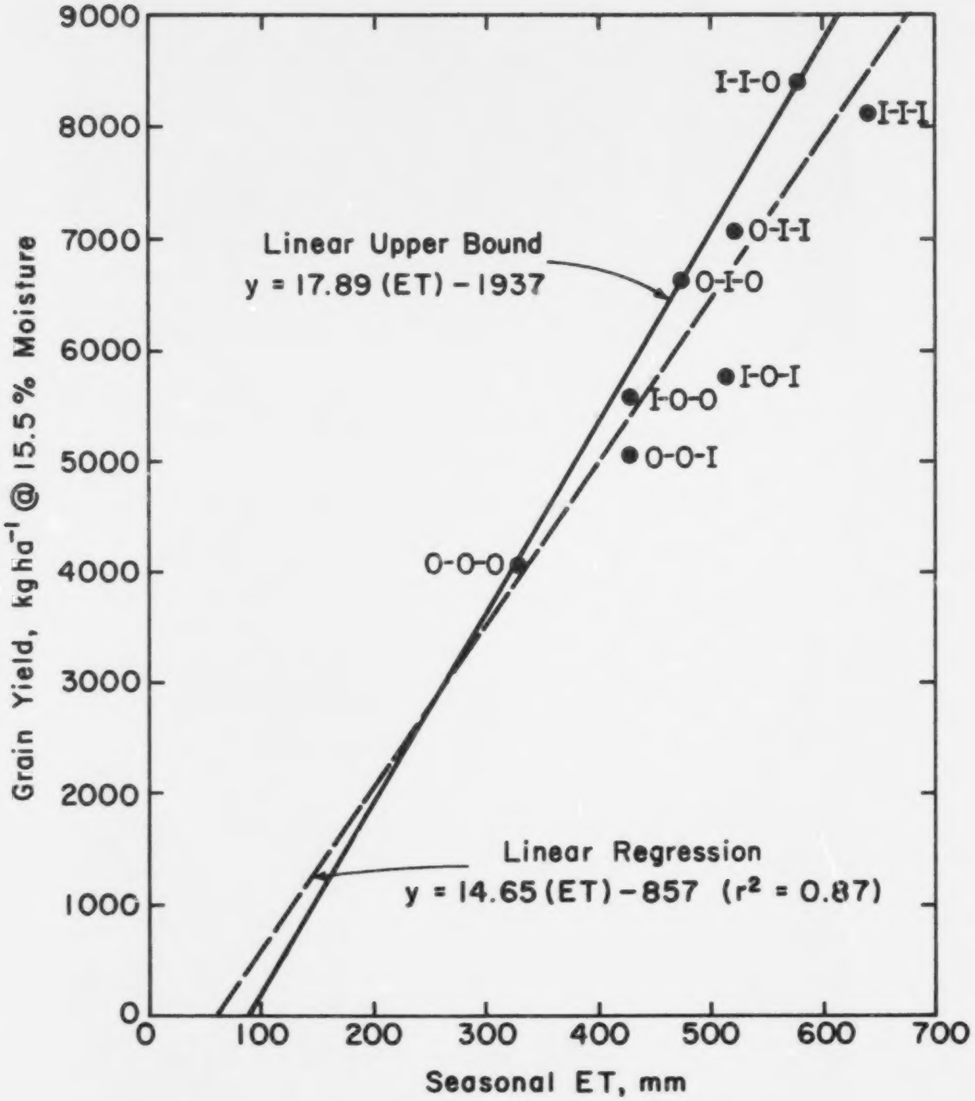


Figure 32. Corn grain yield versus ET: average for each treatment.

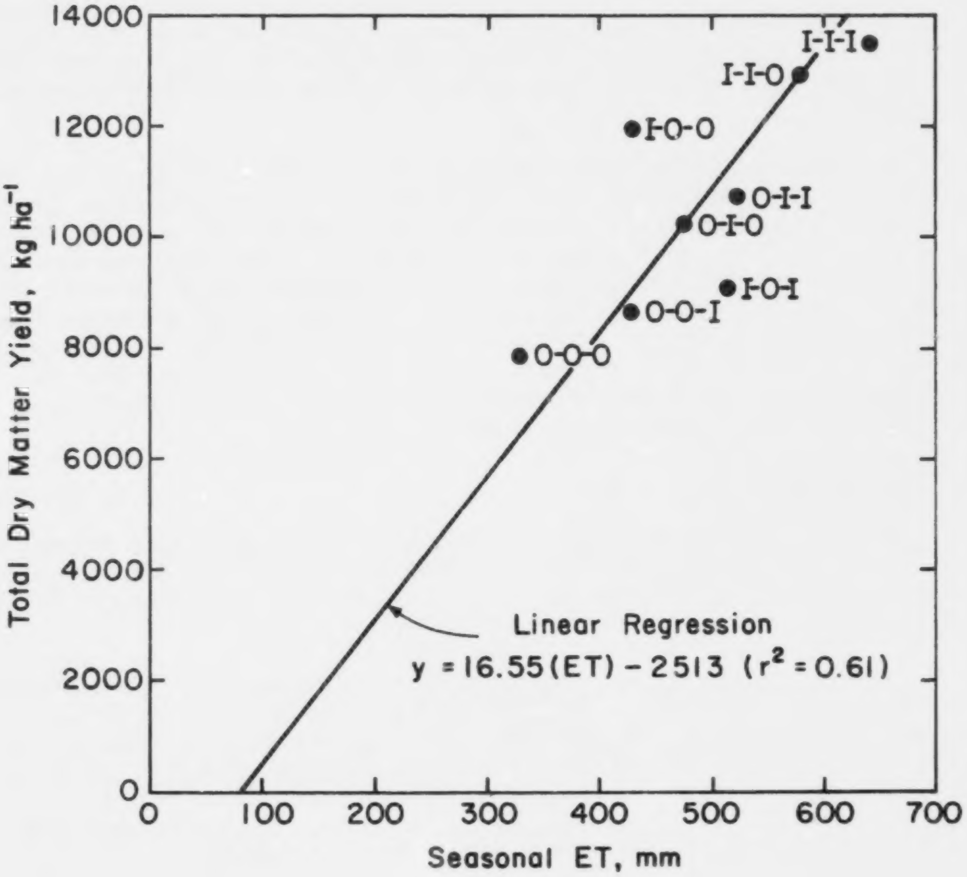


Figure 33. Corn dry matter yield versus ET: average for each treatment.

In other words, it is hypothesized that the genetic pattern of root elongation and proliferation of pinto beans will, in fact, result in the extraction of stored soil water throughout the growing season in a time related pattern which will constitute an optimal ET deficit sequence, provided that: (a) the soil profile is sufficiently deep for full root development, with moderately high water holding capacity and no structural impairment; (b) the entire profile is at field capacity when the crop is planted; and (c) little or no water is applied to the soil during the growing season. These conditions were met in Treatment 0-0-0 with the possible slight violation in two of the plots where the soil profile was only a little more than 200 cm deep in places.

As the infinite combination of possible irrigation regimes could not be tested in the experiment, it is possible that slightly higher yields would be attainable for a given quantity of ET. However, the high soil salinity, the inadvertent early stressing and pest problems would probably be a greater limitation on yield than the irrigation regime. The average yield of the highest yielding treatment approximated the valley average, while the individual highest yield was well above the valley average (approximately 25 percent higher) and higher than those of the better neighboring farmers.

Grain Yields

Grain yields and the analysis of variance are summarized in Tables 8 and 9, respectively. The variance for the irrigation treatments was partitioned into individual degrees of freedom to assist in analyzing treatment effects.

The effects of each irrigation treatment on grain yield are clearly seen in Figure 34. At point 0-0-0 all plots were irrigated the same until the start of the vegetative stage. Treatment 0-0-0 received no additional irrigations from this date. At point I-0-0 only the pollination stage received an irrigation and so on with -I- designating irrigation and -0- designating no irrigation during a particular growth stage.

Grain yields for the treatments that were irrigated during the vegetative stage (the dashed lines in Figure 34) were higher (see Table 9) than the average for treatments not irrigated during the vegetative stage (the solid lines in Figure 34). Maximum yields were obtained when the corn was irrigated during both the vegetative and pollination stages (I-I-0). Continued irrigation through the grain filling stage (I-I-I) was of no additional value. Partitioning of the variance associated with those treatments receiving irrigation during the vegetative stage (B treatments in Table 9) showed that the variance was associated primarily with the pollination irrigations and little was associated with irrigation during grain filling. In a similar

TABLE 8. THE EFFECT OF IRRIGATION TREATMENT ON THE YIELD OF GRAIN (kg/ha AT 15.5% MOISTURE)

Treatment	Rep I	Rep II	Rep III	Rep IV	Mean
0-0-0	3162	3429	3528	5678	3949*
0-0-I	5941	4380	5294	4582	5049*
I-0-0	4615	4433	6105	7199	5588*
I-0-I	5901	4942	5663	3570	5769*
0-I-0	7131	5144	8880	5014	6542
0-I-I	4775	8481	4917	7092	7067
I-I-I	8301	6555	10051	7544	8113
I-I-0	10956	8644	6214	7796	8403
Mean	6348	6126	6707	6060	6310

* Yield lower than I-I-0 treatment at 0.05 level.

way the variance of the grain yields (Table 9) for treatments not irrigated during the vegetative stage was associated largely with the pollination stage irrigation rather than with the grain filling irrigations (compare 0-0-0 vs. 0-I-0, 0-0-I vs. 0-I-I). The results show that irrigations during the pollination period had a much greater effect than those during either the vegetative or the grain filling period.

The relative importance of irrigation during each of the three growth stages is of interest when considering water-use efficiency. When only one growth stage was irrigated beyond crop establishment, the best treatment was the one receiving an irrigation during the pollination period (0-I-0). The results clearly demonstrate the importance of irrigation during the pollination stage and confirms the widespread observation that the pollination period is "critical" with respect to water deficits and yield response. This stage should receive the highest priority when allocating irrigation water.

TABLE 9. ANALYSIS OF VARIANCE FOR YIELD OF GRAIN

Source of variance	df	SS‡	MS‡	F
Total	31	121.00		
Replication	3	2.04	0.68	0.26 NS
Treatment	7	64.90	9.28	3.57*
A vs B	1		13.86	5.33*
0-0-0 I-0-0				
0-0-I I-0-I				
0-I-0 I-I-I				
0-I-I I-I-0				
within A	3	24.26	8.08	3.10*
(0-0-0+0-0-I)vs (0-I-0+0-I-I)	1		21.26	8.18*
(0-0-0 vs 0-0-I)	1		2.42	0.93 NS
(0-I-0 vs 0-I-I)	1		0.55	0.21 NS
within B	3	26.84	8.95	3.44*
(I-0-0+I-0-I)vs(I-I-I+I-I-0)	1		26.61	10.23†
(I-0-0 vs I-0-I)	1		0.06	0.02 NS
(I-I-I vs I-I-0)	1		0.17	0.07 NS
Error	21	54.60	2.60	

Std. Dev. = 1.61

C.V. = 25.5%

L.S.D. = 2372 kg/ha

* significant @ 0.05
† significant @ 0.01
‡ x 10^6

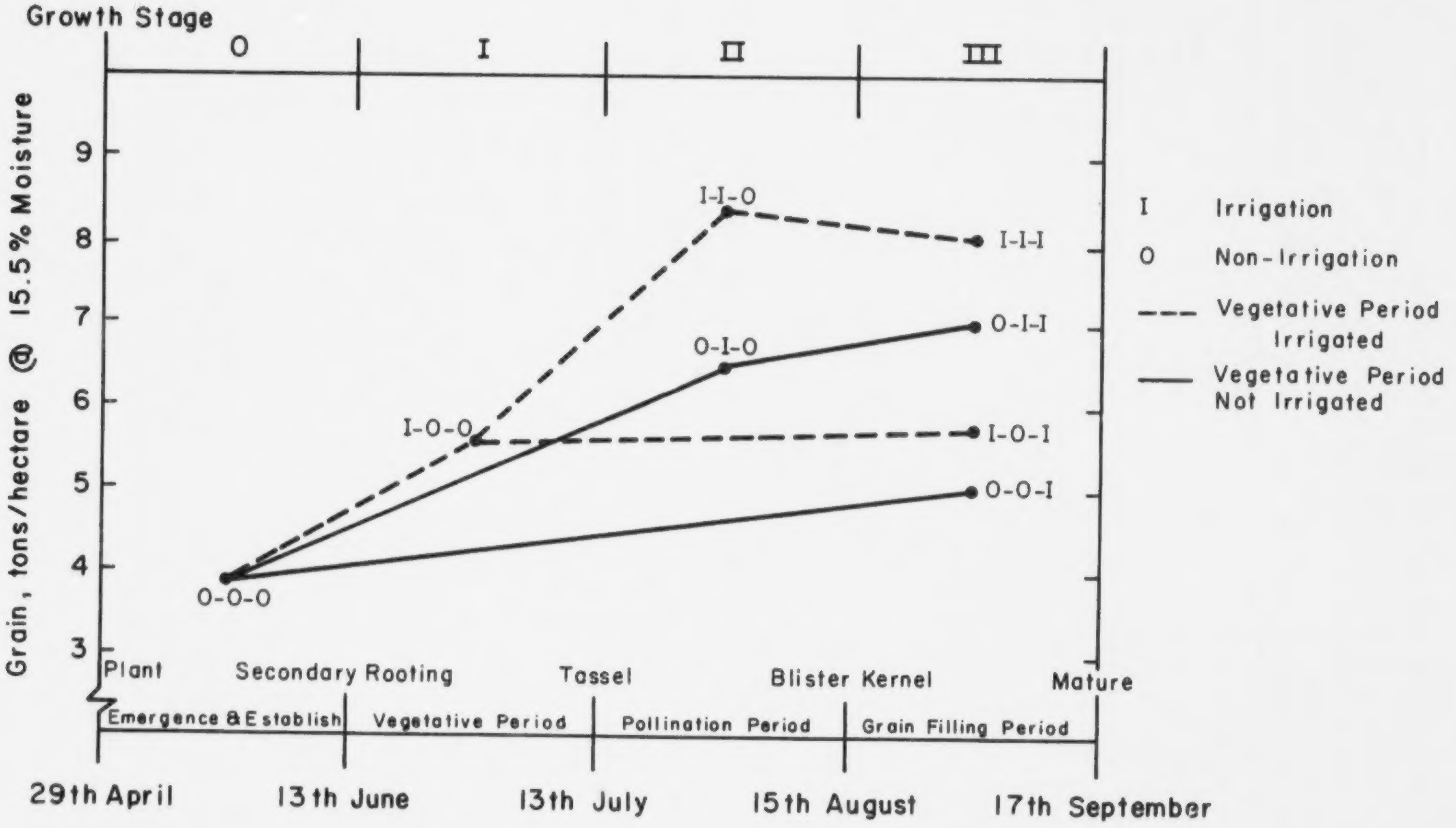


Figure 34. The effects of irrigation treatments on grain yield.

The vegetative period is seen in Figure 34 and Table 9 to be the next most important growth stage to be irrigated, whereas irrigation during the grain filling stage had little or no benefit on grain yield. This phenomenon was also reported by Stewart et al. (1975), who noted that in similar experiments with corn, late irrigation had either no effect or a negative effect on grain yield. The lack of benefit from the last irrigation may be due to a lower need for water during this stage. It may be that the corn plant can obtain sufficient moisture from its own tissues or by drawing on soil moisture from its extensive root system so that an imposed moisture stress did not occur during this last stage of development. It is also possible that a reduction in respiration occurred when the root-zone was kept moist during the highly active period of grain filling. It is evident that when adequate moisture is present during the previous stage, a water deficit is tolerable in the grain filling period without causing grain yield losses. Under similar conditions, the elimination of irrigation during this stage of development could amount to substantial savings in water.

The suggestion has been made that early stress may have a tendency to condition the plant against damage from stress at a later stage as far as grain yield is concerned. Stress occurring in the vegetative stage forces the plant to develop a more extensive root system which helps to meet the water requirements needed during ear development. Denmead and Shaw (1960) reported that early moisture stress, which reduces the size of the assimilation surface at the time of ear development, may have little effect on grain yield; while stress imposed after the ear has emerged has a more direct negative effect by reducing the rate of assimilation during a critical period when photosynthesis is being used for grain production.

Forage (Dry Matter) Yields

The literature reviewed in Section 4 indicates that dry matter production is directly proportional to ET and that the timing of deficits has no effect. The distribution of the data points in Figure 33 would appear to support this view; however, the averages tend to mask some of the scatter obtained in the individual replications (see Appendix E, Figures E-1 to E-8). In a crop such as corn, where the grain makes up a high proportion of the weight of dry matter (40 to 56 percent on a dry weight basis for the treatment averages in this experiment), it would appear reasonable to speculate that an ET deficit particularly detrimental to grain yield would have a correspondingly detrimental effect on dry matter yield.

Forage (dry matter) yields were determined by harvesting a portion of each plot at the time the crop was normally harvested for ensilage. The grain was well into the dent stage of development at harvest (September 17). Yield results are shown in Table 10.

An analysis of variance of total dry matter yield is shown in Table 11. The treatment variance was partitioned into individual degrees of freedom to compare irrigation treatments.

Figure 35 clearly shows the effect of the various irrigation treatments on the yield of total dry matter. There was a highly significant beneficial effect from irrigating during the vegetative stage (Table 11, group A vs. group B). Differences in yield between the pollination stage and grain filling irrigations were not signficant at the 0.05 level although the pollination stage irrigation appeared to contribute slightly more than irrigation during grain filling (Figure 35).

The three high yielding treatments, I-I-I, I-I-0 and I-0-0, were all irrigated during the vegetative stage and the yield of the I-0-0 treatment was 11.95 T per ha. However, for some unexplainable reason, the yield of the I-0-I irrigation treatment was only 9.07 T per ha. It is difficult to explain why irrigation during the grain filling stage would cause a decrease in total dry matter yield. Neither the N nor the soil salinity level deviated from their means sufficiently to explain the diverse results.

Analysis of variance (Table 11) reveals that treatments 0-0-0, 0-0-I, 0-I-0 and 0-I-I were not significantly different and yielded much below treatments receiving an irrigation in the vegetative stage, with the exception of treatment I-0-I. Dry matter yields for treatments I-0-0, I-I-0 and I-I-I were not found to be significantly different.

If water is limiting and only one growth stage is to be irrigated, these results indicate that the most efficient water-use treatment for forage production should be one such as I-0-0 which received irrigation only during the vegetative period. The elimination of irrigation during both the pollination and grain filling stages saved 50.1 cm of water (irrigation plus rainfall) without a significant reduction in yield. The results demonstrate the greater importance of irrigation during the vegetative stage for forage production.

If water is available to irrigate through two growth stages, the vegetative and pollination periods should be the most beneficial. By eliminating the last period of irrigation during the grain filling stage (I-I-0), a savings of 24.5 cm of water applied

TABLE 10. THE EFFECT OF IRRIGATION TREATMENT ON TOTAL DRY MATTER YIELD (METRIC T/ha, OVEN DRY)

Treatment	Rep I	Rep II	Rep III	Rep IV	Mean
0-0-0	6.08	7.18	8.34	9.91	7.88*
0-0-I	12.21	7.35	10.24	6.07	8.97*
I-0-I	6.89	10.98	9.35	9.06	9.07*
0-I-0	10.49	7.28	13.57	9.54	10.22*
0-I-I	9.62	12.19	11.09	9.95	10.71
I-0-0	10.96	10.16	12.41	14.26	11.95
I-I-0	12.21	12.12	10.20	17.26	12.94
I-I-I	11.62	11.41	15.35	15.59	13.49
Mean	10.01	9.83	11.33	11.45	10.65

* Yield lower than I-I-I treatment at 0.05 level.

was achieved without a significant reduction in yield from the maximum. The vegetative stage was clearly the more critical period with respect to dry matter production. This differs from grain production, where the pollination stage was of greater importance. This relationship concurs with the findings of Denmead and Shaw (1960), Robins and Domingo (1953), and Kiesselbach (1950), who also found that increasing moisture stress during the vegetative stage of growth reduced dry matter production.

Relationships Between Grain and Dry Matter Yields

In attempting to trace the effect of water stress during the various stages of growth and in formulating appropriate models, researchers are faced with the problem that grain yield can be measured only after crop maturity. On the other hand, many of the classical studies relating dry matter yield to ET were carried out by harvesting the forage at different stages of maturity. One way of approximating the effect of stress on grain yield may be by tracing the effects of stress on dry matter yield and then relating grain yields to dry matter (Neghassi, 1974).

TABLE 11. ANALYSIS OF VARIANCE FOR YIELD OF DRY MATTER

Source of Variance	df	SS†	MS†	F
Total	31	230.00		
Replication	3	17.37	5.79	1.22 NS
Treatment	7	113.04	16.15	3.40*
A vs B	1		46.90	9.89
0-0-0 I-0-I				
0-0-I I-0-0				
0-I-0 I-I-0				
0-I-I I-I-I				
within A	3	19.60	6.53	1.38 MS
within B	3	46.55	15.52	3.27*
(I-0-I)vs (I-0-0+I-I-0+I-I-I)	1		41.64	8.79†
(I-0-0+I-I-0+I-I-I)	2	4.90	2.45	0.52 NS
Error	21	99.50	4.74	

Std. Dev. + 2.18

C.V. + 20.44%

L.S.D. = 3.2 metric T/ha

*significant @ 0.05

†significant @ 0.01

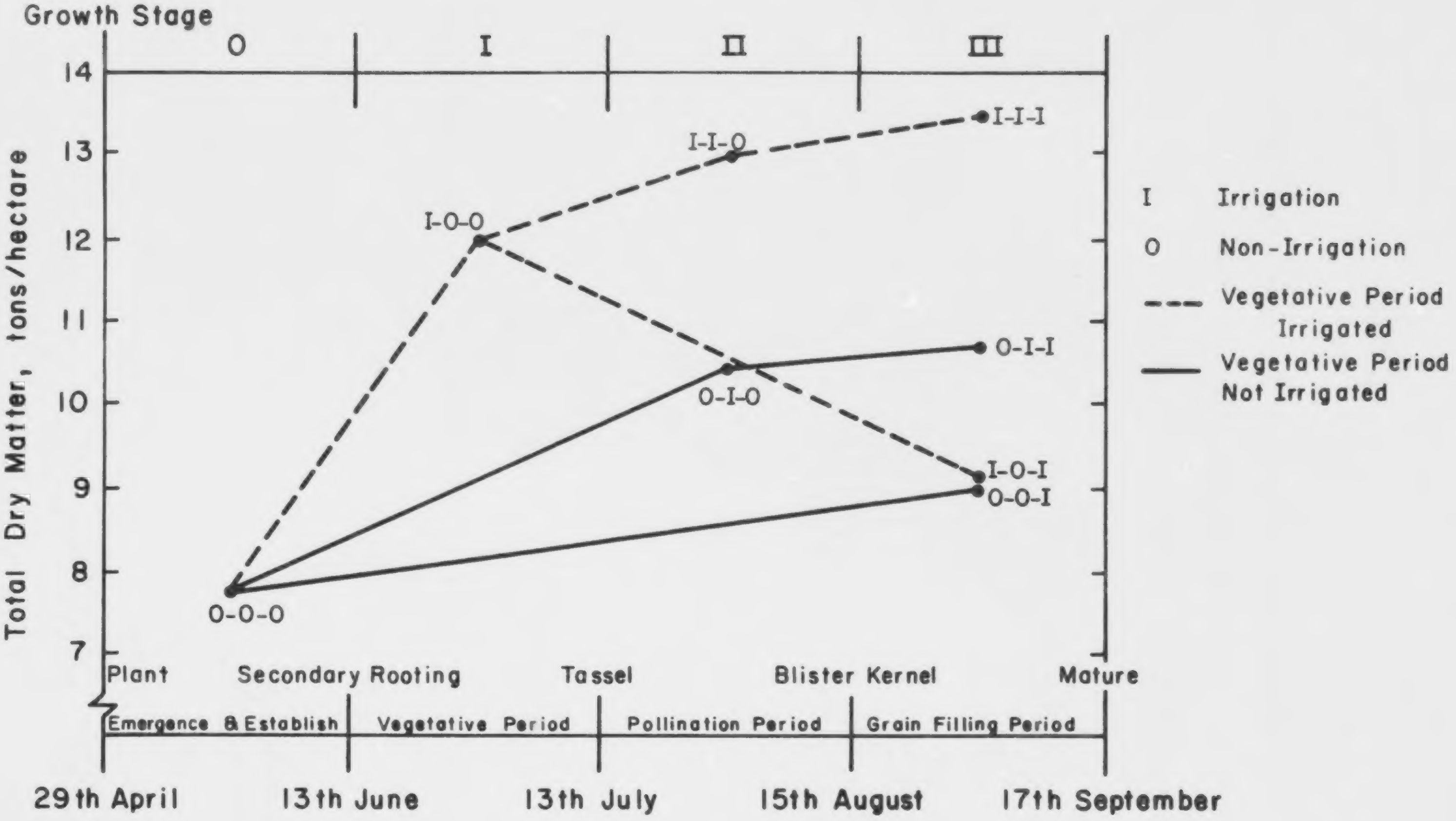


Figure 35. The effects of irrigation treatments on dry matter yield.

The relationship between grain yield and dry matter yield is plotted on Figure 36. The relationship is obviously linear, with all but two of the data points falling within a fairly confined band on each side of the adjusted regression line. Excluding the two most deviant data points, the linear regression equation is:

$$y_G = 0.557\ y_{DM} + 370 \qquad (r^2 = 0.59) \ldots\ldots\ldots (31)$$

where y_G is the grain yield and y_{DM} is the dry matter yield. The regression line has been adjusted slightly in Figure 36 to pass through the origin, in accordance with the plots shown by Neghassi (1974).

To use this function to predict grain yield from a successful dry matter yield model, however, would be to ignore the effects of stress at different stages of growth. In fact, close examination of Figure 36 indicates that some irrigation regimes are far more conducive to dry matter production compared to grain production, and vice versa. Within a particular treatment, the relationship between grain and dry matter yield is basically linear (for example, Treatment I-0-0). However, this treatment and Treatment 0-0-0 obviously favor dry matter production much more than say Treatments 0-I-0 and 0-I-I, the data from which are mostly on the other side of the regression line, favoring grain production. The remaining treatments do not show any particular trend. The implication is that crops receiving water only in the early growth stages will yield comparatively more dry matter per unit of water than any other irrigation regime, which is illustrated in Figure 37, where average dry matter water use efficiency has been plotted against grain water use efficiency. The units of kilograms per hectare-millimeter of water have been used to provide physical meaning. (To be strictly correct, they could be corrected to dimensionless units of efficiency in percent by dividing by 100.) The data fall into two groups, in which Treatments 0-0-0 and I-0-0 show a high efficiency in terms of dry matter production, while treatments 0-I-0 and I-I-0 in particular show a high efficiency in terms of grain production. The remaining treatments decline in efficiency of both grain and dry matter production. Treatment I-0-I, which has the lowest efficiency in both areas, nonetheless falls on the "grain" side of a hypothetical line through the origin dividing the two groups of points. This perhaps indicates that while the severe stress during the pollination period (without any preconditioning) had a drastic effect on grain yield, the effect on dry matter yield was even more marked. Earlier, it was suggested that this might be the case because the grain component makes up a substantial portion of the dry matter yield. It also suggests that the classical studies relating dry matter yield to ET, in which the forage was harvested at different

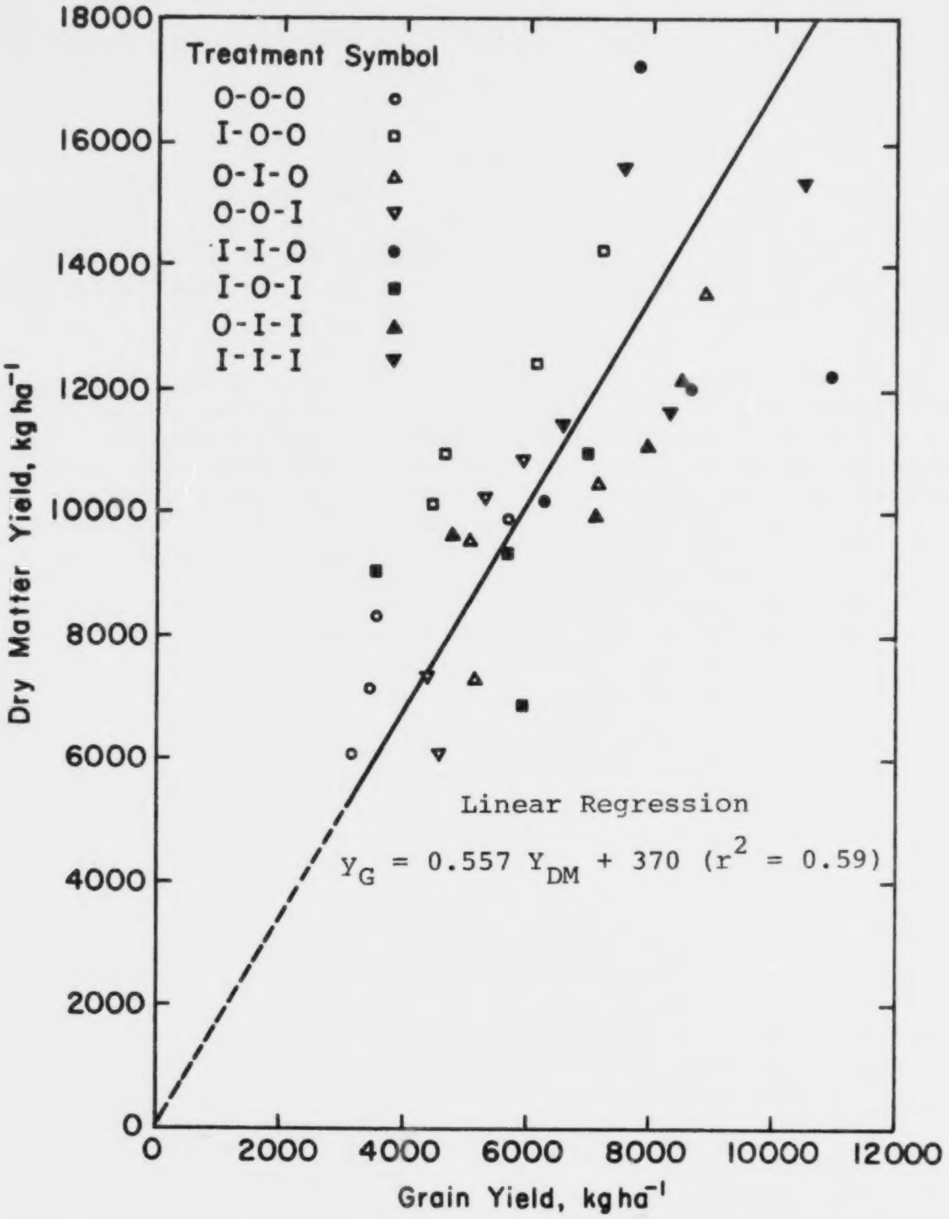


Figure 36. Relationship between dry matter yield and grain yield for corn.

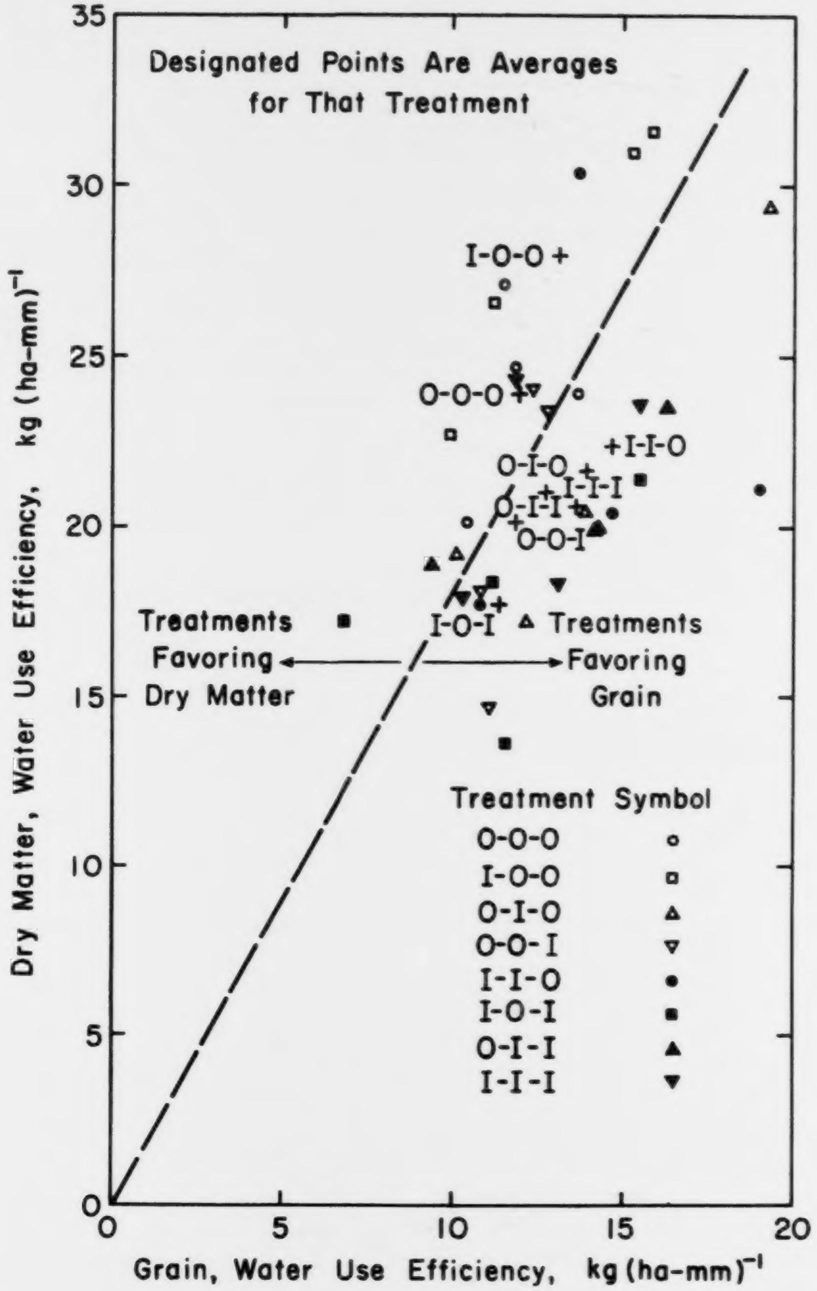


Figure 37. Water use efficiency of corn: dry matter versus grain.

stages of maturity, may not be particularly appropriate to the field situation. The timing of deficits on the yield of forage harvested at maturity may warrant further investigations, particularly with regard to the plant physiology.

Water Production and Water Use Efficiencies

The water production efficiencies (also called water applied efficiencies) and water use efficiencies for grain and dry matter production are given in Table 12 for the various irrigation treatments. The water production efficiencies are inversely related to yield, with maximum production efficiencies occurring with the lowest yielding treatments. The high efficiencies were due to the corn plants ability to utilize existing soil moisture and to withstand long periods of drought stress.

TABLE 12. EFFICIENCY OF IRRIGATION WATER APPLIED AND OF TOTAL MEASURED WATER USE IN TERMS OF YIELD PER UNIT OF WATER

	Water Production Efficiency*		Water-Use Efficiency†	
Treatment	Dry Matter kg/cm	Grain kg/cm	Dry Matter kg/cm	Grain kg/cm
0-0-0	684	343	239	144
I-0-0	436	204	279	149
0-I-0	280	179	216	150
0-0-I	242	136	202	129
I-I-0	244	158	224	160
I-0-I	165	105	176	128
0-I-I	182	120	206	140
I-I-I	174	105	201	137

*Values represent the average yield divided by cm. of seasonal water applied by irrigation and from rainfall.

†Values represent the total yield divided by measured seasonal ET obtained by the water balance approach.

The water use efficiencies are directly related to yield with maximum efficiencies occurring in the higher yielding treatments (Table 12). The irrigation treatments which approach the maximum water use efficiency were irrigated during the most critical stages of growth, particularly during the vegetative stage for dry matter yield and during the pollination stage for grain yield as discussed previously.

A comparison of the relationship between yield and the amount of water supplied to the plants, and the relationship between yield and ET, has been illustrated in Figures 38 and 39 for grain and dry matter yields, respectively. The amount of water supplied to the plants is defined in this case as the sum of the depth of irrigation water applied, plus rainfall, plus the end of season depletion from field capacity in the range 0 to 190 cm (or to the underlying shale if at a depth of less than 190 cm). This assumes that all plots were watered to field capacity at the beginning of the season to a depth of 190 cm (or to shale). The validity of this assumption could not be quantitatively checked but it appears highly probable.

The difference between water supply as defined and ET for Treatment 0-0-0 would be anticipated to be smaller than for any of the other treatments, as no additional irrigation water was applied after the establishment period. In fact, Treatment 0-I-0 was found to have approximately the same difference, indicating that all of the water applied in this treatment was consumed. Treatment I-0-0 was found to have a smaller difference, created by the anomaly discussed above, but this was ignored. Therefore, the ET abscissa was displaced to the right, compared to the water supply abscissa, by an amount equal to this difference. The yield versus water supply function was drawn as a best fit through the plotted points.

In the case of grain yield versus ET, the function has been drawn as the linear upper bound in the same manner as in Figure 32. With the displaced abscissa shown in Figure 38, the yield versus water supply function is tangential to the yield versus ET function at the point corresponding to Treatment 0-0-0 but diverging away from the function at higher values of water supply. This substantiates the point made in Section 4 that the difference between linear and curvilinear production functions is due to the choice of abscissa. The functions shown in Figure 38 have exactly the same form as those presented by Stewart and Hagan (1973) and shown in Figure 7.

Because of the scatter of data, the drawing of a dry matter production function is more difficult and less precise. However, a yield versus water supply function has been drawn through the dry matter data in Figure 39 which is tangential to the yield versus ET function (with the displaced abscissa) at lower values

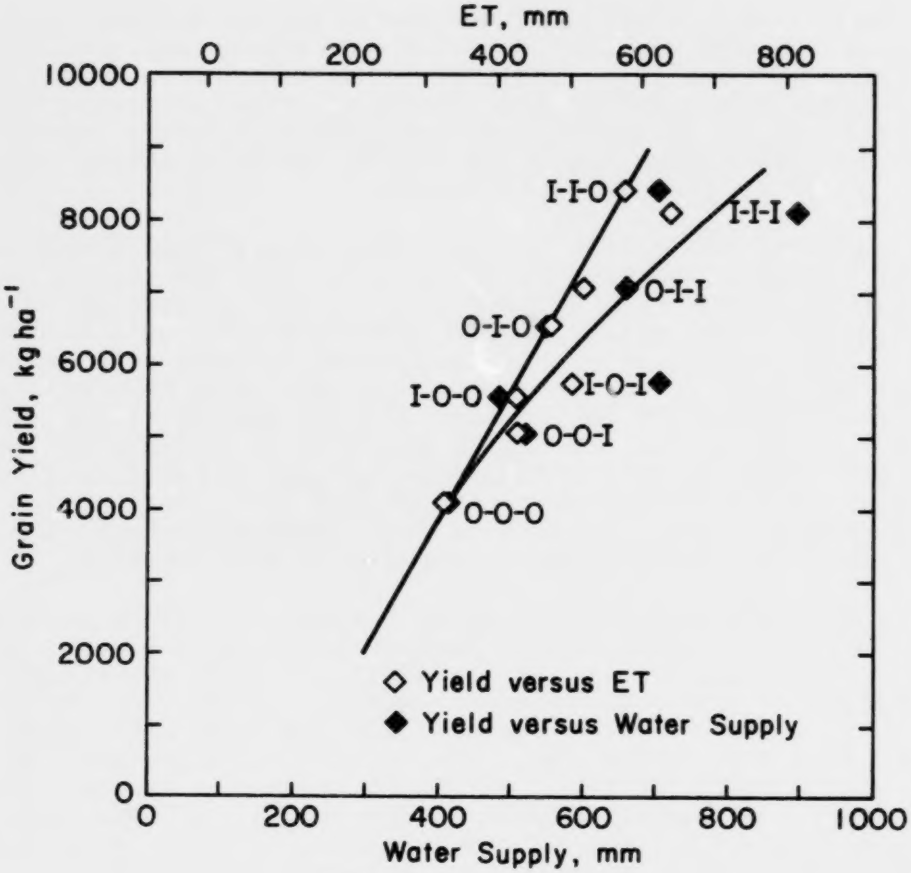


Figure 38. Relationship between grain yield and ET and between grain yield and crop water supply, for corn.

of water supply. Again, the data confirms that the difference in the two functions is due to the choice of abscissa.

WHEAT

As the experimental control in the wheat experiment could only be described as "fair," the results are presented more for completeness and to confirm existing recommendations than for any subsequent detailed analysis. The results are shown in Figure 40, where grain yield is plotted against ET computed as described in Section 6. As only 10 plots were included in the experiment, the results of the individual plots are shown, rather than the average results. The numerical results are given in Appendix F.

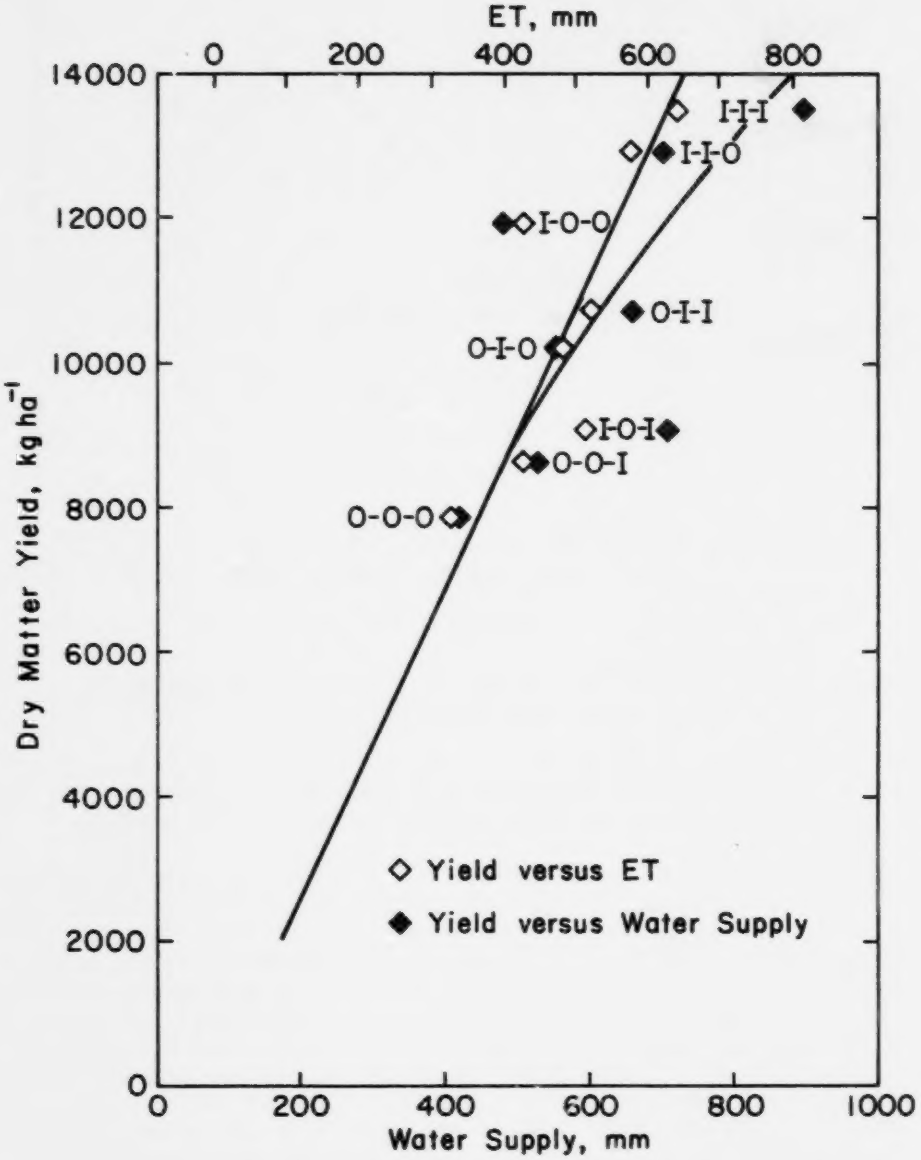


Figure 39. Relationship between dry matter yield and ET and between dry matter yield and crop water supply, for corn.

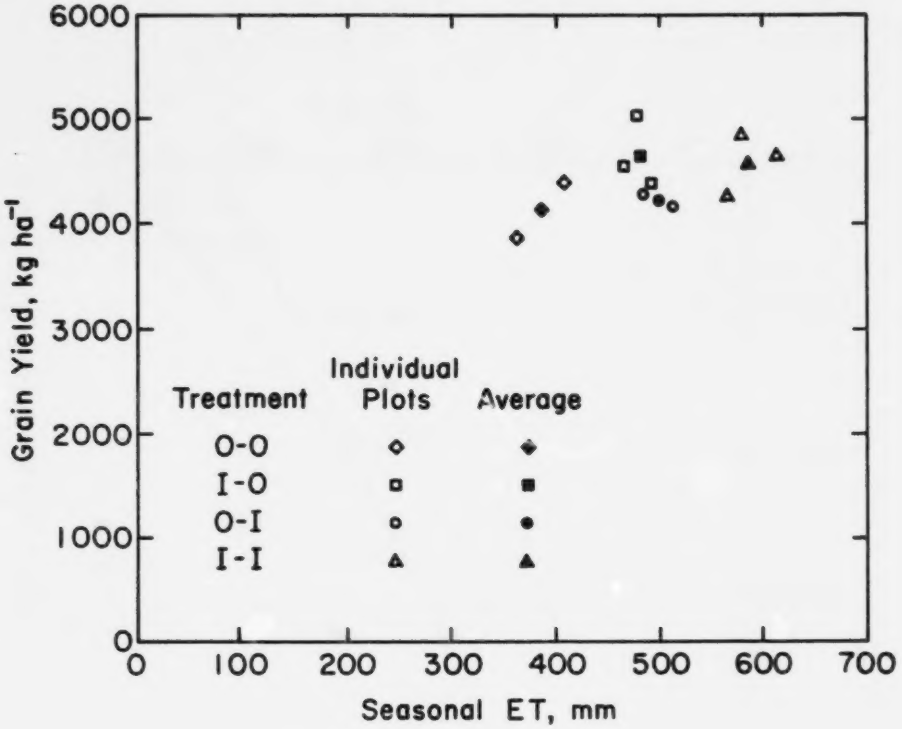


Figure 40. Variation of grain yield of wheat with seasonal evapotranspiration.

From many studies carried out on wheat, Salter and Goode (1967) were able to draw the general conclusion that:

> During the shooting and earing stages of growth, when the development of the reproductive organs is taking place, the wheat plant is especially sensitive to soil moisture conditions. Shortage of water in the soil, and also atmospheric drought, had the greatest effect at this time in terms of loss of yield, and in many experiments this loss was irreversible and could not be regained by providing optimum moisture conditions at other growth stages. Irrigation and rain have also generally been shown to have the maximum beneficial effect during shooting and earing.

Observation of the results shown on Figure 40 substantiates this conclusion in respect to the effect of moisture stress during the earing stage (when the ear is emerging from the tube formed by the leaf sheaths). No differentiation in moisture stress was made during the shooting stage (the stage of elongation of internodes). It is particularly noticeable that irrigating in the grain-filling period is of little value. The I-I Treatment shows very little improvement in yield over the I-0 Treatment, and Treatment 0-I shows very little improvement over 0-0. Irrespective of the earlier treatments, the later irrigation was virtually wasted. The early irrigation (I-0) showed a substantial increase in yield over the higher of the 0-0 treatments in only one of the three plots, although the average of the three I-0 treatments is substantially higher than the average of the two 0-0 treatments. Although the early irrigation was of benefit, it would appear that the stress during the shooting stage may even have limited the effectiveness of this irrigation.

SECTION 9

FERTILIZER USE EFFICIENCY

The fertilizer treatments of the study were designed to insure crop growth and to evaluate salt transport. The principal study area was Field II, which was used to grow corn. The fertilization of the alfalfa, wheat, and Jose Tall Wheatgrass was to promote crop vigor and evaluate salt transport from the bottom of the root zone.

Due to a paucity of data from some of the drains surrounding each plot in the test area, as a result of an experimental design that only supplied sufficient irrigation water to satisfy the evapotranspiration requirements of the crop, it is not possible to evaluate salt transport in all the test plots. The best data are available for salt transport and fertilization on Plots 22 and 23 located in Field II because these two plots contained the vacuum extractors. The discussion in this section will be an evaluation of the data for nitrate and nitrogen use and nitrate transport in Plots 22 and 23.

As indicated in an earlier section, one goal of the fertilizer treatment was to achieve a level of nitrogen in the surface soil of either 100 ppm or 60 ppm on the plots in Field II. The fertilizer applications indicated in Table 1 were based on soil chemical analysis (Table 4). Plot 22 was a low level treatment plot (60 ppm) and Plot 23 was a high level (100 ppm) Plot 23 received no fertilizer because laboratory analysis of the soil samples from this plot showed it was already at the desired fertility level (99 ppm), whereas Plot 22 required a fertilizer application of 488 kg per hectare of NH_4NO_3 to increase the soil nitrogen level from 21 ppm of NO_3-N to 60 ppm.

A nitrogen balance was computed for both plots which considered applied, extracted, residual, transported and native nitrogen sources. Applied nitrogen totaled an equivalent of 488 kg/ha for Plot 22 and 0 kg/ha for Plot 23. The application requirement was based on surface soil analysis and treatment level.

The transported nitrogen was computed using volumetric and quality data for the soil water extracted by the vacuum lysimeters. The leachate volumes collected in each plot have been expressed as a surface depth and tabulated in Table 13 for both Plots 22 and 23. The indicated depth of water represents the water collected between consecutive dates. For example, in Plot 23 on 6/18/76 the depth is 7.2 mm. This represents the water extracted between 6/9/76 and 6/18/76. The vacuum lysimeter for Plot 22 was inoperative for part of the season and the water balance had to be completed using the change in soil moisture storage between the beginning and end of the growing season. The average daily flux was 1 mm for the 63 days of operation of Plot 22, while the seasonal average daily flux is estimated to be 0.9 mm. For the comparable period, the average daily flux in Plot 23 was 0.62 mm. The seasonal average daily flux from Plot 23 for the 116 day test period was 0.45 mm.

The soil-water extracted each week was analyzed for nitrates along with the other salts being studied. The nitrate values for the weekly extracts are summarized in Table 14. Inspection of the data for each plot does not indicate major differences in the nitrate concentrations for the soil water extracts early in the season for each plot. The nitrate levels begin to decrease in the extracts for Plot 23 after July 23, 1976. The soil water is being extracted at a depth of roughly 3 feet below the soil surface, roughly the bottom of the root zone. This would indicate an increased usage of nitrogen by the crop. At this time, the roots should also be reaching their maximum development. The data indicate an improved fertilizer usage with increased crop growth stage.

The volumetric data in Table 13 and the concentration data in Table 14 were combined to calculate the total nitrate salt transport. The transport calculation assumed a uniform concentration for the flux equal to the water chemistry analysis at the end of the extraction period. The calculated transported nitrate was summed for each interval to give a total transport value for the plot.

The data in Table 15 show that 24.2 kg/ha nitrate were lost from Plot 22 in the first 63 days of operation and 21.8 kg/ha were lost from Plot 23 in 116 days of operation. When reduced to an average value, Plot 22 lost 0.38 kg/ha per day and Plot 23 lost 0.19 kg/ha per day. With the levels of fertilization being 60 ppm for Plot 22 and 100 ppm for Plot 23, the data from the extraction indicates that a closer scrutiny of the irrigations is required.

If the total transport is considered for the first 63 days in Plot 23, the average transport value is 0.31 kg/ha per day, which is roughly equivalent to the loss in Plot 22. The data for Plot 23 when compared to Plot 22 show that the majority of the nitrate loss occurs early in the season. A total of 2.1 kg/ha was lost after July 23, 1976, which means a total of 19.7 kg/ha were lost prior to this time in 63 days.

TABLE 13. LEACHATE VOLUMES COLLECTED IN VACUUM EXTRACTORS FROM PLOTS 22 AND 23 DURING 1976

Plot 22 (0-0-I)		Plot 23 (0-I-I)	
Date	Depth Collected (mm)	Date	Depth Collected (mm)
5/20/76	19.3	5/20/76	5.8
5/25/76	4.6	5/05/76	3.9
6/1/76	.4	6/1/76	5.5
6/9/76	18.4 I*	6/9/76	4.5 I*
6/18/76	8.19	6/18/76	7.2
6/25/76	5.74	6/25/76	2.5
7/2/76	2.72	7/2/76	2.2
7/9/76	2.0	7/9/76	4.5
7/23/76	2.80	7/23/76	3.1 I
Total Flux	64.15	8/12/76	5.2 I
Ave. Daily Flux for 63 days	1 mm	8/24/76	3.4 I
		8/31/76	2.7 I
		9/14/76	1.7 I
		Total Flux	52.2
		Ave. Daily Flux for 116 days	.45 mm

Seasonal E_t - 463 mm	Seasonal E_t - 510 mm
Applied IRR - 282 mm	Applied IRR - 509 mm
Rain (May 3-July 19) - 35 mm	Rain (May 3-Sept. 19) - 67 mm
Total Applied - 349 mm (282+67)	Total Applied - 576 mm (509+67)
Soil Moisture Seepage - 220 mm	Total Loss - 562 mm (510+52)
Total Est. Flux - 106 mm (349+220-463)	Net - 14 mm (576-562)
Ave. Daily Flux - 0.9 mm	
Irrigation applied prior to July 23 - 42 mm	

*I - Indicates Irrigation

TABLE 14. NITRATE CONCENTRATION IN LEACHATE FOR PLOTS 22 AND 23

Plot 22			Plot 23		
Date	NO_3		Date	NO_3	
	ppm	meq/l		ppm	meq/l
5/20/76	42	.69	5/20/76	65	1.05
5/25/76	36	.58	5/25/76	63	1.02
6/1/76	11	.17	6/1/76	51	.83
6/9/76	18	.30	6/9/76	16	.26
6/18/76	53	.86	6/18/76	54	.87
6/25/76	40	.69	6/25/76	53	.86
7/2/76	79	1.27	7/2/76	58	.94
7/9/76	85	1.38	7/9/76	70	1.14
7/23/76	34	.55	7/23/76	32	.51
Extractor Inoperative			8/12/76	36	.59
			8/24/76	5.3	.09
			8/31/76	2	.03
			9/14/76	0	0

The flux values and nitrate concentrations in Plot 23 were lower after July 23 than earlier in the season. This occurred even though the supply of water was being increased by irrigation during this time period. Increases in plant growth activity and deeper penetration of roots into the soil at this stage of growth probably account for the reduced loss of water and lower nitrate concentrations.

The distribution of nitrates in the soil is shown in Table 16 for Plots 22 and 23 for Fall 1976. The values are fairly uniform in both plots with high values being in the surface soils and a reduction in value which is fairly uniform down to 6 feet. At 6 feet, the nitrogen levels increase. The higher concentrations in the surface soils are a result of fertilization and native nitrogen due to organic matter. The higher nitrate

TABLE 15. TOTAL NO_3 IN LEACHATE FROM PLOTS 22 AND 23.

Plot 22		Plot 23	
Date	NO_3 (kg/ha)	Date	NO_3 (kg/ha)
5/20/76	8.1	5/20/76	3.7
5/25/76	1.6	5/25/76	2.4
6/1/76	0	6/1/76	2.7
6/9/76	3.3	6/9/76	.7
6/18/76	4.3	6/18/76	3.8
6/25/76	2.3	6/25/76	1.3
7/2/76	2.0	7/2/76	1.3
7/9/76	1.7	7/9/76	3.1
7/23/76	.9	7/23/76	.9
Extractor Inoperative		8/12/76	1.9
Total	24.2 kg/ha	8/24/76	.2
		8/31/76	0
		9/14/76	0
		Total	21.8 kg/ha
Ave. 63 days - .38 kg/ha day		Ave. 116 days - .19 kg/ha day	
.085 kg-N/ha day		.042 kg-N/ha day	

TABLE 16. NITRATE DISTRIBUTION IN PLOTS 22 AND 23 IN FALL OF 1976

Plot 22			Plot 23		
Depth	NO_3		Depth	NO_3	
	ppm	kg/ha (1)		ppm	kg/ha (1)
0-1	8	39.4	0-1	8	39.4
1-2	2	9.8	1-2	4	19.7
2-3	1	4.9	2-3	3	14.8
3-4	3	14.8	3-4	4	19.7
4-5	7	34.5	4-5	4	19.7
5-6	4	19.7	5-6	4	19.7
6-7	10	49.3	6-7	13	64.1
Total		172.4	Total		197.1

(1) Assumes soil bulk density of 1.56 gm/cm^3 based on numerous field measurements for plots 22 and 23.

concentations at the lower depths may reflect that nitrogen was transported in previous seasons to these lower depths.

The total nitrate in the soil profile was calculated assuming a soil bulk density of 1.56 gm/cm^3. One other source of nitrogen in the soil is the nitrogen due to organic matter in the soils.

The extraction of nitrogen by the crop is needed to complete the analysis. The percentage of nitrogen in corn leaves was analyzed to obtain an estimate for nitrogen uptake (Table 17). It was assumed that the leaves would adequately represent the dry matter. The nitrogen in the grain had a value roughly equal to that found in the dry matter. The percent nitrogen in the grain was calculated as percent protein divided by 6.25 Total uptake of nitrogen by corn is summarized in Table 18. There was an estimated 233 kg/ha extracted in Plot 22 and 207 kg/ha in Plot 23. The additional yield in Plot 22 was responsible for the higher uptake values. From Table 17 the percentage of nitrogen present in the leaf samples for Plots 22 and 23 are nearly equal.

TABLE 17. PERCENT NITROGEN IN LEAVES OF CORN PLANTS

Plot	N,%	Plot	N,%
17	1.08	33	1.19
18	1.40	34	1.01
19	0.06	35	1.28
20	1.08	36	1.26
21	0.82	37	1.12
22	1.44	38	1.64
23	1.51	39	1.37
24	1.36	40	1.14
25	0.92	41	1.30
26	1.04	42	1.06
27	1.16	43	1.11
28	1.09	44	1.55
29	0.70	45	1.23
30	1.49	46	0.93
31	1.52	47	1.18
32	1.27	48	1.51

Note-100 leaves taken from rows to be harvested when approximately 75% of field showed silk emergence (5th of August). Second leaf from top ear taken and analyzed for total N by semi-micro Kjeldahl method.

The nitrogen balance is summarized in Tables 19 and 20 for Plots 22 and 23. In Plot 22 there was an initial soil nitrogen content of 96 kg/ha and an equivalent application of 200 kg/ha with an uptake by the crop of 233 kg/ha, a residual in the soil of 39 kg/ha and a loss of 10 kg/ha in the leachate. The nitrogen balance looks very good. The nitrogen loss in the leachate was roughly 3 percent of the total available nitrogen.

In Plot 23, the plant extracted an equivalent of 207 kg/ha, there was 45 kg/ha remaining in the soil and 5 kg/ha were lost in the leachate. Since no nitrogen was supplied as fertilizer, the nitrogen had to be extracted from the initial soil nitrogen, which amounted to 490 kg/ha. The nitrogen balance is very poor. The estimated nitrogen loss in the leachate is probably higher than indicated; however, the only significance that can be assigned to this balance would be that leachate nitrogen loss is still only a small percentage of the available nitrogen.

Nitrate transport was studied in Plot 22 and Plot 23 in an effort to evaluate fertilizer use efficiency. The data indicate that very little nitrate was lost through leaching from the plots. The majority of the nitrate in the leachate was lost early in the growing season. The nitrate loss pattern closely follows the flux patterns of the soil water. Considering the experimental design for the 1976 irrigation season, the results are not surprising. Essentially, the plots, when irrigated, were supplied with only sufficient moisture to satisfy the water requirements of the plants. Therefore, there was very little deep percolation occurring, and consequently, very little nitrogen moved below the root zone. This result emphasizes the importance of highly efficient irrigation practices in achieving better fertilizer use efficiency, along with reducing nitrates in the underlying groundwater reservoir.

TABLE 18. NITROGEN UPTAKE BY CORN

Plot 22		
Dry Matter	- 10850 kg/ha	
% N in Dry Matter	- 1.44	156.2 kg/ha
Grain Yield	- 5941 kg/ha	
% N in Grain[1]	- 1.3	77.2 kg/ha
		233.4 kg/ha
Plot 23		
Dry Matter	- 9622 kg/ha	
% N in Dry Matter	- 1.51	145.3 kg/ha
Grain Yield	- 4776 kg/ha	
% N in Grain	- 1.3	62.1 kg/ha
		207.4 kg/ha

[1] Estimate based on assumption of 8% protein in grain.

TABLE 19. PLOT 22 SUMMARY NITROGEN BALANCE

Initial Soil N as NO_3	96 kg/ha	
Total Applied N	200 kg/ha	
Final Soil N as NO_3		39 kg/ha
Estimated Loss in Leachate (1)		10 kg/ha
Plant Extracted N		233 kg/ha
	296 kg/ha	282 kg/ha

(1) Assumes a loss of 0.085 kg -N/ha day for 116 days

TABLE 20. PLOT 23 SUMMARY NITROGEN BALANCE

Initial Soil N as NO_3	490 kg/ha	
Total Applied N	0 kg/ha	
Final Soil N as NO_3		45 kg/ha
Estimate Loss (1) in Leachate		5 kg/ha
Plant Extracted N		207 kg/ha
	490 kg/ha	257 kg/ha

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(1) Assumes a loss of 0.042 kg -N/ha day for 116 days.

Section 10

IMPACT OF CROP PRODUCTION FUNCTIONS UPON ALLOCATION AND USE OF IRRIGATED WATER

The literature reviewed and the results presented to this point indicate, for a wide range of crops, that the relationship between yield and ET is linear. In the case of crops where the reproductive organ or associated product is harvested (as in cereal crops, soybeans, cotton and some vegetable crops) the linear relationship represents the upper bound on yield for varying amounts of ET, at least for those crops reported herein. Further research is required to establish the linearity (or otherwise) of the yield functions for other crops.

The substantiation of the linearity of crop production functions with respect to ET has a profound effect on determining the optimal allocation of irrigation water and this in turn will affect irrigation practices. The extent and implications of these effects on yields and return flows will be the subject of the remainder of this report.

Two situations may be faced in problems of water allocation. In Case (I), irrigation water is limited, while land is available. This is the case where, for example, wells, water rights or on-farm reservoirs limit the water supply to an amount insufficient to produce the maximum yield from the available land area. In Case (II), irrigable land is limited, while water is available at a price. In this case, sufficient water is available to supply the full irrigation requirements of the available land area.

A third possibility is that both water and land are limited and in such a ratio that the maximum yield cannot be attained on all of the available area. However, this problem reduces to that of the first case.

The role of crop production functions in determining the optimal water allocation will be investigated first by considering the irrigation water to be perfectly applied (i.e., crop needs fully satisfied, with no losses). The relevant production function is then yield versus ET. In Case (I), this will determine the optimal land area to irrigate, while in Case (II) this will determine the optimal quantity of water to be supplied.

The determination of optimal allocation of irrigation water under the assumption of perfect application is only a theoretical first step in order to provide a conceptual background for the real problem of allocation under field conditions. In this case, which will be the next considered, loss of a portion of the applied water will occur, the magnitude of this loss depending on the inherent ability of the irrigation system to apply the desired amount of water uniformly and on the management practices associated with the use of the water.

In many areas, rainfall provides a substantial contribution to the total water requirement of an irrigated crop. The effects of this contribution on the determination of the optimal water allocation is discussed next. The effect of rainfall can be expected to be most significant under conditions where dryland cropping is possible, where the costs of crop production are going to be incurred irrespective of whether irrigation water is applied or not.

The analysis outlined above is based on the consideration of a single crop. The results are next extended to multiple crop decisions.

Departures from the linear upper bound of yield-water use production functions have been shown to be due to the timing of water deficits. This implies that water management means more than simply ensuring that the crop is supplied with an amount of water exceeding its ET requirements during the course of the growing season. An understanding of the nature of crop production functions is a useful tool in on-farm water management. This understanding becomes particularly important for conditions where water is limited relative to the land area. In this case, every unit of water saved means that additional land can be brought under irrigation, or that more of the available water is actually transpired by the crop, with profits consequently increased.

ALLOCATION UNDER CONDITIONS OF PERFECT WATER APPLICATION

Perfect water application is intended to imply that water is applied and is available to the crops in amounts exactly equalling the ET requirement and that all of the ET requirement comes from the applied water, with none from stored soil moisture or rainfall. Losses due to inefficiency or nonuniformity are not considered to exist in this instance and additional water for leaching is not required. This condition may be considered as the ideal which will never be achieved in the field; however, the concept does allow the first step to be taken towards investigating the effect of actual production functions on the allocation of irrigation water. The concept implies a linear yield versus ET function. Under certain irrigation regimes (for example, under the Israeli conditions reported by Shalhevet et al., 1976) yield versus applied water functions are also found to be linear, in which case the same analysis applies, subject to one condition to be discussed subsequently.

Optimal Land Area

Under conditions where water is limited relative to the available land area, Case (I), the amount of water allocated to each unit of land (i.e., the seasonal depth of application) automatically determines the area of land that will be irrigated,

$$\text{i.e., } A_I = \frac{Q}{x} \; \ldots\ldots\ldots\ldots \; (32)$$

where A_I = area of land irrigated,

Q = total quantity of water available, and

x = depth of water applied.

To determine the optimal depth of water application (x_{opt}), the objective becomes to

$$\text{maximize } P = (O_I - I_I)A_I \; \ldots\ldots\ldots\ldots \; (33)$$

where P = net revenue

O_I = output (gross revenue) per unit of irrigated area

I_I = input (costs) per unit of irrigated area

and A_I = area irrigated.

The output in the objective function may be expressed as:

$$O_I = v_c y \; \ldots\ldots\ldots\ldots \; (34)$$

where v_c = gross unit value of crop (\$/kg),

and y = yield per unit area (kg/ha).

As the yield may be represented by the linear production function

$$y = a + bx, \; \ldots\ldots\ldots\ldots \; (35)$$

the output can be expressed as:

$$O_I = a' + b'x, \quad \ldots\ldots \quad (36)$$

as v_c is a constant.

The input may be expressed as:

$$I_I = c_1 + c_2 + c_3 + \ldots + c_n \quad \ldots\ldots \quad (37)$$

where the c_i = cost of any operation associated with producing and disposing of the crop, per unit area.

For many field crops, the cost of these operations per unit area are:

c_1 = cost of seedbed preparation
c_2 = cost of seed
c_3 = cost of sowing
c_4 = cost of fertilizing
c_5 = cost of pesticides
c_6 = cost of interrow cultivation
c_7 = cost of irrigation (labor, energy & fixed costs of system)
c_8 = cost of water
c_9 = cost of harvesting
c_{10}= cost of disposing

Many of the above costs are affected to varying degrees by the yield obtained, while some are constant per unit area for a given crop. For example, c_1 and c_6 are constant and c_5 has been taken as constant although conceivably at low rates of water application where water conservation becomes critical; the value of c_5 for herbicides could possibly increase. The cost of sowing, c_3, could vary a minimal amount due to increased sowing rates, but is essentially constant.

The cost of seed, c_2, is dependent on the sowing rate, which in turn depends on the anticipated yield. The cost of fertilizer, c_4, of harvesting, c_9, and of disposing of the harvested product, c_{10}, all depend on the anticipated or actual yield. If yield per unit area falls below a certain minimum, c_9 may be constant.

The cost of irrigating has three components: labor, energy and the annual fixed cost of the irrigation system. The quantity of water to be applied during the course of the season is fixed.

If this quantity of water were applied over a large area, there would generally be fewer irrigations at a higher cost per irrigation than if the water were applied over a smaller area, receiving more irrigations at a lower cost per irrigation. The costs will be approximately the same, and will depend only on the quantity of water applied. For example, with furrow and most sprinkler irrigations, a larger area will require more sets per irrigation, but will not be able to be watered as frequently as a smaller area. The total number of sets, which is the principal component of labor costs, will be exactly equal if the flow rate is the same in either case, but could vary slightly for different flow rates. With more capital intensive systems, such as center-pivot or trickle irrigation, the labor input to the actual process of irrigating is low and is fairly constant for a given quantity of seasonal irrigation water. Variable costs of pumping (energy plus maintenance) will also be dependent on the quantity of water applied. The fixed cost of the irrigation system will depend on the area and will generally tend to be cheaper per unit area for a larger area than a smaller area. However, as the quantity of available water is fixed, the range in which the optimal land area can be expected to lie is limited, and hence, the cost per unit area would not vary greatly.

The cost of water, c_8, includes only the charge for the water. Energy costs have been included in c_7 and will be constant, as the total volume of water is fixed. Water charges may be constant per unit volume or may be on an escalating scale.

In many instances, the sum of the costs of irrigating (c_7 plus c_8) is constant per unit volume of applied water and, for simplicity, advantage will be taken of this fact in later analyses. For the present case, however, the costs are separated so that the effect of an escalating scale of charges for water may be evaluated where appropriate.

The fixed cost of machinery, which has been included in the above costs as appropriate, may be expected to decrease per unit area as land area increases. However, similar to the discussion on irrigation system fixed costs, if the range of area irrigated is between say 20 and 30 ha, or between 2,000 and 3,000 ha, the fixed cost of machinery per unit area will vary little.

The argument may be advanced that the fixed costs of machinery move in quantum increments and that the marginal cost of farming one additional hectare is much lower than the average cost per hectare, as much of this average cost is made up of fixed costs. A more rigorous method of analysis may, therefore, be to consider all costs at contract rates, in which the charges are generally made up of a fixed cost plus a variable cost depending on area or yield. This analysis has been carried out in Appendix G, in which it is shown that the objective function is the same as obtained in the following analysis. This means that the same result is obtained irrespective of the method of pricing.

The cost components making up I_I may be expressed as follows, in $ per ha, by substituting a + bx for the yield, y, and collecting terms:

$c_1 = a_1$
$c_2 = a_2 + b_2x$
$c_3 = a_3$
$c_4 = a_4 + b_4x$
$c_5 = a_5$
$c_6 = a_6$
$c_7 = a_7 + b_7/A_I$
$c_8 = a_8/A_I$
$c_9 = a_9 + b_9x$
$c_{10} = a_{10} + b_{10}x$

where all the a's and b's are constants, and A_I is the area on which the fixed quantity of water, Q, is applied.

The variation of c_i with x may not necessarily be linear (although this is usually the case), but this representation is adequate for the argument as the variation will always be monotonically increasing. The expression as a linear function is for the sake of simplicity.

Therefore, the objective becomes to:

$$\text{maximize } P = [a' + b'x - (a_i + b_ix + b_j/A_I)]\, A_I \text{ . . . . (38)}$$

where $a_i = a_1 + a_2 + a_3 + a_4 + a_5 + a_6 + a_7 + a_9 + a_{10}$

$b_i = b_2 + b_4 + b_9 + b_{10}$

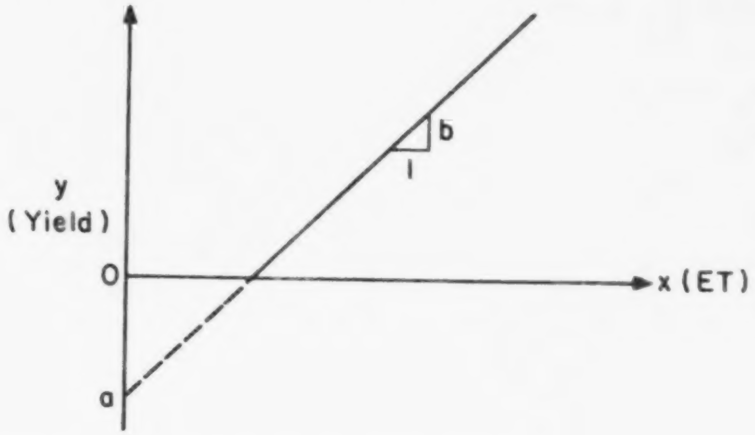
$b_j = a_8 + b_7$

Recognizing that $x = Q/A_I$, where Q is a constant, the objective function may be expressed as

$$\text{maximize } P = a'A_I + b'Q - (a_iA_I + b_iQ + b_j) \text{ . . . . . . (39)}$$

$$P = (a' - a_i)\, A_I + (b' - b_i)\, Q - b_j \text{. . . . . . (40)}$$

Now, a' (= $v_c a$) is always a large negative number as a finite amount of ET is required to produce any yield. These relations are illustrated in the following diagram:



The term a_i is made up of positive numbers where costs are constant per unit area or possibly small negative numbers (compared to a') where costs depend on yield. The terms b'Q, b_iQ and b_j are all constants.

Therefore, as $(a' - a_i)A_I$ is always negative, the maximum profit will be obtained when the area of land is kept as small as possible within the constraints.

The foregoing analysis can be qualitatively deduced by recognizing that all costs either stay the same (c_7, c_8, c_{10}) or increase (the remaining terms) as land area increases. At the same time, because of the negative value of a (which was the condition referred to immediately prior to this subsection), supplying the full ET requirement (x_{max}) yields a proportionately higher yield than some fraction of x_{max}. In this case, x_{max} is equivalent to ET_{max}, the lowest value of ET for which maximum yield is attained (but not necessarily the maximum value of ET).

The constraints have not previously been discussed, but are: (a) land area; (b) maximum depth of applied water; (c) capital; (d) attainable irrigation efficiency; (e) labor; and (f) flow rate.

If the land area is to be kept as small as possible, in this ideal case the only constraint that comes into force is to keep the maximum depth of applied water (x_{max}) to that which produces the maximum yield (Y_{max}). This amount of water is then x_{opt}.

The area to be irrigated is, therefore:

$$A_{opt} = \frac{Q}{x_{opt}} \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (41)$$

Optimal Water Supply

In irrigating a fixed area (as defined, for example, by water rights or physical limitations) where water is available at a price, the problem is to determine whether to supply the crops' full water requirements or, if the cost of supplying the water is high, perhaps to supply less than the full requirement. The seasonal depth of water applied will determine the total volume of the irrigation water supply.

To determine the optimal depth of water application, the objective is to:

$$\text{maximize } p = O_I - I_I \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (42)$$

where $p = P/A_I$ = net revenue per unit area

O_I = output (gross revenue) per unit area

I_I = input (costs) per unit area

Again, $O_I = v_c y$ and $I_I = c_1 + c_2 + c_3 + \ldots + c_n$ as before,

where $c_1 = a_1$

$c_2 = a_2 + b_2 x$

$c_3 = a_3$

$c_4 = a_4 + b_4 x$

$c_5 = a_5$

$c_6 = a_6$

$c_7 = a_7 + b_7 x$

$c_8 = a_8 + b_8 x$

$c_9 = a_9 + b_9 x$

$c_{10} = a_{10} + b_{10} x$

The terms c_2, c_4, c_7, c_8, and c_{10} all vary with yield and hence are functions of x which varies linearly with y. The variation of the c_i with y may not be linear functions, but in all cases they will be monotonically increasing functions, so the effect will be the same.

The objective can, therefore, be generalized as:

$$\text{maximize } p = a' + b'x - (aj + b_j x) \text{ . . . . } (43)$$

$$\text{where } aj = \sum_{i=1}^{10} a_i \text{ and } b_j = b_2 + b_4 + b_7 + b_8 + b_9 + b_{10}$$

$$\text{i.e., maximize } p = a' - a_j = (b' - b_j)\ x \text{ . . . . } (44)$$

As in the previous case, $a' - a_j$ will be negative. In order to make a profit, it will be required that:

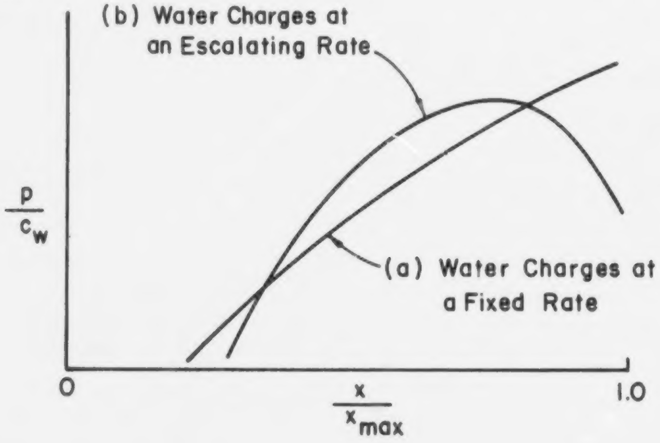
$$(b' - b_j)\ x > |a' - a_j| \text{. . . . . } (45)$$

and also that $b' > b_j$.

If these two conditions are satisfied and the coefficient b_j is constant (does not vary with x), then the maximum profit is obtained when x is a maximum, subject to the constraint that $x \leq x_{max}$. (If the two conditions were not satisfied, irrigation would not be feasible.) The depth of water to apply for maximum profit is x_{max} and the volume to apply is $Q = A_I x_{max}$.

The only case in which b_j could vary with x is for the charge for water. If the charge for water is on an escalating rate, i.e., successive volumes of water have a higher price per unit, a point may be reached where $b_j > b'$. The optimal depth of water to apply is that for which the last increment retains $b_j < b'$. An example computation using typical production costs in relation to the crop being grown, i.e., \$100 per 1,000 m^3 (\$123 per acre-foot) for wheat before the depth of water applied should be less than x_{max}.

The effect of an escalating rate of water charges compared to a constant rate per unit of water may be represented on a dimensionless plot as follows:



where c_w is the charge for the volume of water corresponding to a given depth of application over a unit area, and the other terms have been defined earlier. The relative position of the two lines will depend on the magnitude of the water charges, while the relative curvature of line (b) will depend on the degree of escalation of the charges. If the escalating charges still only represent a small portion of total production costs, line (b) will approach the shape of line (a). A numerical example illustrating this concept is also included in Appendix G.

Deviation from the Ideal

The foregoing two subsections demonstrate that if irrigation water could be applied in amounts just equal to crop ET (no losses), and that if all of the crop ET is derived from the irrigation water (no available soil moisture or rainfall), then the maximum profit-making policy is to make available for crop consumption that amount of water per unit area which gives maximum yield per unit area.

This conclusion is based on a linear production function with a positive intercept on the abscissa. The concept developed forms the basis for the discussion which is to follow. Application inefficiencies have been shown to cause the production function to deviate from a linear relationship when yield is plotted against applied water. The next problem is to investigate whether this deviation makes a significant difference regarding this conclusion.

If rainfall and available soil moisture make a significant contribution to the crop water supply, the yield versus applied water function may have a negative intercept when projected on the abscissa. Irrigation is then supplementary to the total crop water supply. The effect of supplementary irrigation on the conclusion drawn from the theoretical case is subsequently investigated.

EFFECT OF APPLICATION INEFFICIENCY

Functional Concepts of Application Efficiencies

In the field situation, decisions on water allocation will be based on yield versus applied water production functions, not yield versus ET functions. That is, in the common situation where the available water supply is inadequate to fully supply crop water needs over the available land area, the available water supply must be divided by the amount of water applied per unit of land to arrive at the total number of land units to be irrigated. The amount of water applied per unit of land will be the ET divided by the application efficiency.

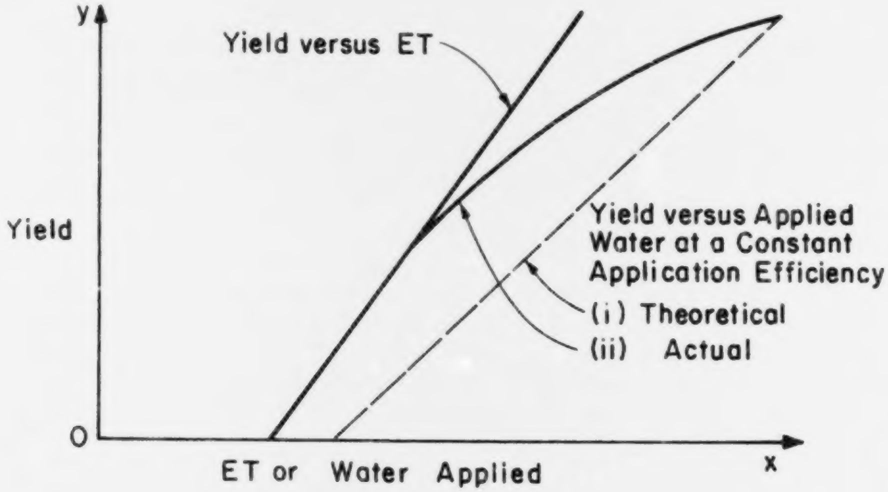
No method of irrigation is capable of exactly supplying the ET requirements of crops. Existing irrigation methods and practices result in application efficiencies consistent with their inherent limitations, which tend to be a function of cost and historical water availability. In the situation where water is abundant compared to the available area of land, the application efficiencies will determine the amount of water needed.

Water application efficiency is defined as the ratio of the amount of water being stored in the root zone of the soil where it can be used by plants to the amount being applied or delivered to the field. The term is a widely used index of the efficiency with which water is being used within an irrigated area, although it is not a complete measure of the effectiveness of irrigation. For example, it is entirely possible to irrigate with an application efficiency of 100 percent and still fall well short of potential yields. The application efficiency fails to indicate the uniformity of water application, or whether enough water has been applied to sustain the crop until the next irrigation. Although an easily defined term, it is often quite misleading to people not thoroughly versed in its implications (Kovda et al. 1973).

Nonetheless, the term is quite useful for comparative purposes, particularly in the common case where excess water is applied to the whole field, with losses occurring due to deep percolation, surface runoff and nonbeneficial evaporation. Bearing this in mind, efficiency of irrigation application may be readily represented on the crop yield-water use functions as shown in Section 8. There it was shown that the yield versus crop water supply function could be plotted tangential to the yield versus ET function by displacing the abscissa. The horizontal difference between the two functions represents the losses, or amount of irrigation water applied that is not consumed by the crop. When the two functions are plotted on the same abscissa, they may no longer be tangential, but rather separated at lower values of ET or water supply, and in this case, the difference between the two functions represents the amount of available soil moisture and rainfall, in addition to applied irrigation water, that is not consumed by the crop. Obviously, difficulties arise in defining the yield versus water supply production function when available soil moisture and rainfall contribute to the crop water supply. These difficulties are discussed in the subsequent subsection.

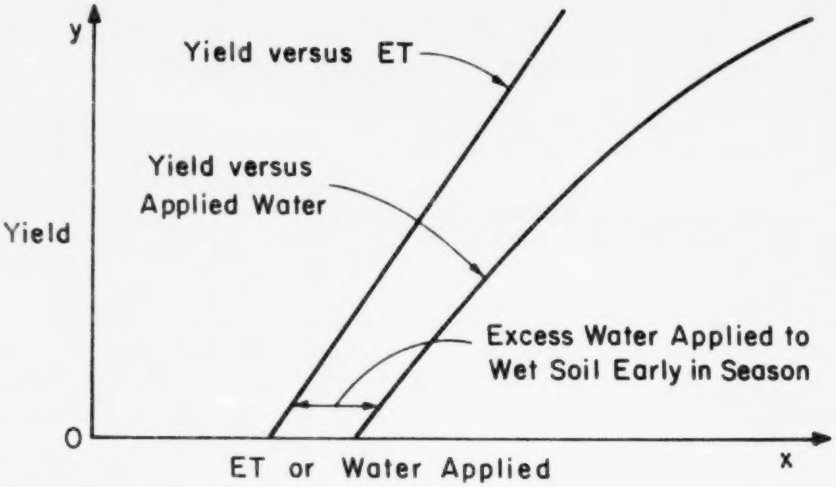
For the two functions to be tangential at low values of ET or water supply, it is assumed that all of the applied water is consumed. This will generally be the case where all of the (low amount of) applied water is provided early in the season. As the crop's root system develops during the course of the season, it will expand to exploit all of the available water in the potential root zone. Of course, if too much water is applied early in the season so that some water percolates below the potential root zone, losses will occur even for a relatively low amount of ET. Similarly, if the water is applied late in the season, the crop will not be able to consume the available water and again losses will occur.

To illustrate a simple case, it may be assumed that water is applied at a constant efficiency during the course of the season. This functional relationship is represented by the dashed straight line as follows:



In reality, however, this relationship is improbable. It could be approximately true if all the losses were removed from the system as, for example, in the case of spray losses from sprinkler irrigation. However, even sprinkler irrigation is subject to deep percolation losses as additional water is applied to overcome the effects of nonuniformity. Considering the deep percolation losses, it may be seen that with a constant application efficiency some of the water applied early in the season which percolates beyond the root zone of the shallow-rooted seedlings may become available to the crop later in the season as the root system expands. This proportion of the loss is, therefore, only temporary. When the seasonal yield versus applied water function is plotted, it may appear as the solid curvilinear function in the above graph. Of course, all of the lines shown represent optimal timing of irrigation applications for the given quantity of water (x).

If excess water were applied to a wet soil early in the season, the resulting production function may be as follows:



Unique and Nonunique Functions

Crop production functions are of limited value unless they are consistently reproducible (and therefore predictable) or at least have the same form. The discussion in the previous subsection of a production function satisfying the two conditions of linearity and a positive x-intercept showed that the same conclusion regarding the allocation of irrigation water is reached irrespective of the slope of the line. If these two conditions are not satisfied, different conclusions could conceivably follow. If the shape of the production function differs from year to year, area to area and farmer to farmer, and if the shape is not predictable, then the optimal allocation of irrigation water is equally unpredictable.

The functions reviewed in Section 4 generally plotted yield against transpiration, evapotranspiration or applied water, depending on the objectives of the research. The yield versus transpiration production function is comparatively unique for a given crop in a given area. Although it will vary slightly from year to year depending on climatic conditions, the form of the function stays the same. The equation for each year could be corrected to reflect advective energy and excess radiation. Arkley (1963) found that a correction based on relative atmospheric humidity serves this purpose and he used this parameter to correct data from different areas. For a given crop, he was able to show a unique linear relationship between dry matter yield and the corrected value of transpiration, irrespective of the area (or country) in which the crop was grown. This relationship would obviously form the ideal basis for a water allocation model were it not for the practical problems involved. Firstly, the linear relationship developed by Arkley (1963) and de Wit (1958) is demonstrated only for dry matter production. (However, as a linear relationship exists as the upper bound of the yield of the reproductive organ of many crops when plotted against ET, it would appear reasonable to suggest that this is also true when plotted against transpiration.) Secondly, at the present time it is exceedingly difficult to measure transpiration under field conditions. Therefore, although the yield versus transpiration function would appear to be unique and readily reproducible, it is of limited practical value due to the difficulty in quantifying the amount of transpiration.

The yield versus ET function is not strictly unique as it will vary slightly even within a given area due to management practices and to variations in climatic conditions from year to year. However, the function will still remain linear and will represent the upper bound on yields for given quantities of water under a given irrigation practice and during a given season. Consistent good management will make the function close to unique for a given area and the function does have the advantage that ET can be computed or measured with a fair degree of facility and accuracy. Therefore, although this function lacks the distinctive uniqueness of the yield versus transpiration function, there is a tradeoff in terms of practicality which makes this function very useful for a comparison of results from different areas. Most of the predictive models reviewed in Section 4 use a relationship between relative evapotranspiration (ET/ET_p) and yield or relative yield (y/Y_{max}).

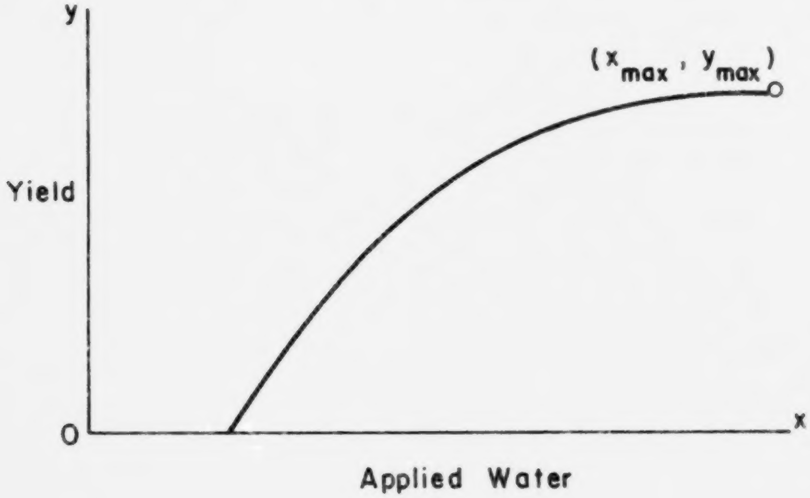
A number of writers have made recommendations on irrigation amounts and timing based on the results obtained from experiments comparing yields to quantities of applied water. These results have been used to compute the quantities of water which should be applied to achieve maximum yields and maximum profits. Although the methodology used is not always sound, as shall be shown in the following section, worse yet the function upon which it is based (yield versus applied water) is so subjective that it is of little value. The function will fluctuate over a wide range, depending on the amount of rainfall during the growing season, the amount of available soil moisture at planting and, not insignificantly, on the water application techniques of the individual irrigator. The contribution of all of these factors to the crop water supply will be influenced by the soil type. Furthermore, transferring the results obtained from research plots to irrigated fields will be unrealistic due to the significant differences in efficiency and uniformity to be expected. Also, the results of the mathematical analysis to which the function obtained is subsequently subjected are very dependent on the form of the mathematical expression used, as will be shown in the following subsection.

In summary, while the yield versus transpiration function may be the ideal on which to base subsequent analysis, the yield versus ET function is the most practical. Although the yield versus applied water function comes closest to representing the field case, its nonuniqueness renders it of little value in obtaining comparative results. However, because it does, in all its variations, represent the field case, an attempt must be made to see if some general conclusions can be deduced from it, with these conclusions being valid over the possible range of the function. This is the subject of the next subsection.

Maximum Yield and Maximum Net Return

Although a unique function cannot be used to represent the relationship between yield and applied water under field conditions, the relationship can be generalized as concave downwards and it is possible to arrive at some general results by considering just the basic shape of this functional relationship, supplemented by some representative costs and returns.

In considering the case of ideal water application (preceding subsection) it was shown that the point of maximum yield and maximum net return corresponded to the same value of ET, viz., that value corresponding to Y_{max}. Conceivably, if the relationship were of the form:



where both the ordinate and abscissa are plotted to a linear scale, the amount of applied water corresponding to the point of maximum net return may be considerably less than that corresponding to the point of maximum yield.

In fitting a functional relationship to yield versus applied water data, it would appear obvious that the function should not be extrapolated beyond the range of the data. Notwithstanding, Shipley (1977) fitted the function:

$$y = a_1 + a_2x + a_3x^2 \quad \ldots\ldots\ldots\ldots \quad (46)$$

to his data and obviously expected this function to hold over a wider range. He hypothesized that the amount of applied water corresponding to the maximum yield could be obtained by setting

$$\frac{dy}{dx} = 0. \quad \ldots\ldots\ldots\ldots \quad (47)$$

and then solving for x. Obviously overlooked is the fact that the fitted function is not a law relating yield to applied water, but rather a curve that happens to fit over the range of data only. For example, the data could just as readily be fitted by the function:

$$y = ax^b \qquad \text{where } 0 < b < 1. \quad \ldots\ldots\ldots\ldots \quad (48)$$

In this case,

$$\frac{dy}{dx} = b\,ax^{b-1}. \quad \ldots\ldots\ldots\ldots \quad (49)$$

$$= 0 \text{ when } x = \infty.$$

The danger of extending the function beyond the range of the data becomes apparent.

The amount of water corresponding to the maximum yield can be obtained from the results presented in Section 8. ET_{max} is designated as that value of ET corresponding to Y_{max} and may be less than the maximum value of ET. The amount of water to apply is

$$x = \frac{ET_{max}}{\eta} - R - ASM \quad \ldots\ldots\ldots\ldots \quad (50)$$

where η = application efficiency,

R = effective rainfall, and

ASM = available soil moisture at planting,

provided that the efficiency is not so low that yield reducing factors due to poor irrigation practices (for example, aeration problems or lodging) come into play.

For irrigation to be profitable, the cost of applying irrigation water must be less than the return from the irrigated product. The point of maximum net return is obtained where the marginal cost of irrigating becomes equal to the marginal return from the irrigated product. This can be analyzed using the method presented by Hogg et al. (1969). Case (II) shall be considered first, as it is easier to analyze and easier to understand.

Case (II): In this case, the land area is fixed, with adequate water available at a price. The expression for net revenue per unit of land area (p) is:

$$p = v_c y - v_w x - c \quad (51)$$

where y = yield per unit area

v_c = value per unit of crop yield

x = quantity of applied water per unit area

v_w = cost per unit of water, and

c = cost per unit area of operations other than those associated with irrigating.

Net revenue is maximized when the derivative of this profit function, with respect to the quantity of irrigation water, is set equal to zero. Assuming for the moment that c is constant, then:

$$\frac{\partial p}{\partial x} = \frac{\partial y}{\partial x} v_c - v_w = 0 \quad (52)$$

Therefore, $$\frac{\partial y}{\partial x} = \frac{v_w}{v_c} \quad (53)$$

This is the result used by Shipley and Regier (1975), by Shipley (1977) and by Stewart and Hagan (1973), although none explain its basis. In general, it is not correct. The value of c (for example, the cost of fertilizing, harvesting and transporting) will rarely be constant, but rather, will be dependent on yield. Some costs will be independent of yield (for example, cultivation), so that c can be expressed generally as:

$$c = k + v_j y \quad (54)$$

where k = constant costs per unit of area, and

v_j = yield dependent costs per unit of crop yield.

Therefore, $$p = v_c y - v_w x - (k + v_j y) \quad \text{. . . . . (55)}$$

$$\frac{\partial p}{\partial x} = v_c \frac{\partial y}{\partial x} - v_w - v_j \frac{\partial y}{\partial x} \quad \text{. . . . . (56)}$$

$$= 0 \text{ when } \frac{\partial y}{\partial x} = \frac{v_w}{v_c - v_j} \quad \text{. . . . . (57)}$$

The yield dependent costs (v_j) must be less than the value per unit of crop yield (v_c) for profitability. In fact, those costs must be considerably less, otherwise the constant costs and water costs would make irrigation uneconomical. They probably constitute only 10 to 30 percent of the value per unit of crop yield, but nonetheless should be included for completeness and understanding.

The equation for net revenue per unit area (Equation 55) may also be expressed as:

$$p = \text{Returns} - \text{Costs}, \quad \text{. . . . . (58)}$$

where $$\text{Returns} = (v_c - v_j)y \quad \text{. . . . . (59)}$$

and $$\text{Costs} = v_w x + k \quad \text{. . . . . (60)}$$

The maximum net revenue is the point where the difference between the Returns and Costs is the greatest, as shown on Figure 41. This point, as derived above in Equation 55 , is where:

$$\frac{\partial y}{\partial x} = \frac{v_w}{v_c - v_j} \quad \text{. . . . . (61)}$$

and hence is the point where a line drawn at a slope of $v_w/(v_c - v_j)$ is just tangential to the y versus x production function (yield versus applied water) as shown in Figure 41. The slope of this line will determine where it is tangential to the production function and, consequently, the optimal depth of irrigation water to apply.

The slope of the line, which hereafter will be called the price ratio (PR), is inherently flat and consequently is tangential to the production function at large values of x. For example, using typical prices and costs for grain sorghum:

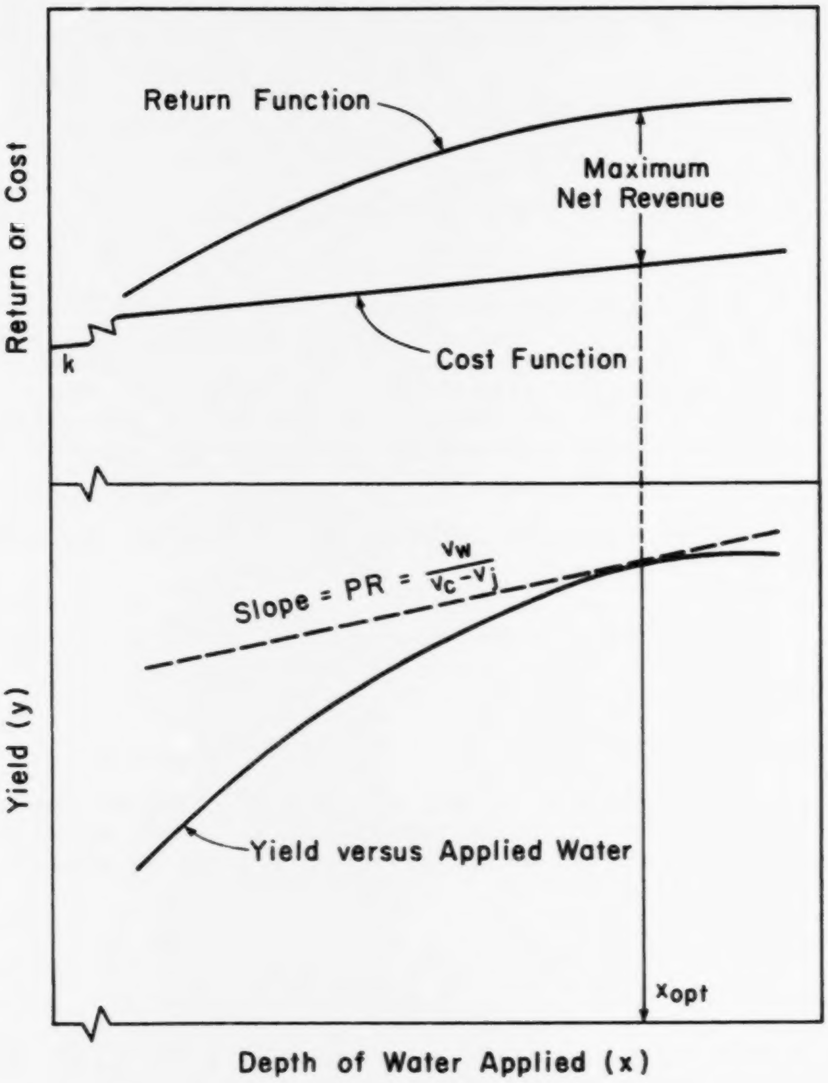

Return Function
Maximum Net Revenue
Return or Cost
k
Cost Function
Slope = PR = $\frac{v_w}{v_c - v_j}$
Yield (y)
Yield versus Applied Water
x_{opt}
Depth of Water Applied (x)

Figure 41. Determining optimal depth of irrigation water to apply where water is plentiful.

v_c = \$0.08 per kg (≃ \$3.50 per cwt)
v_w = \$0.25 per ha-mm (≃ \$2.50 per ac-in)
v_j = \$0.02 per kg (≃ \$0.50 per bushel)
then PR = 4.17 kg per ha-mm (= 0.833 cwt per ac-in).

Applying this, for example, to Shipley's (1977) production function for grain sorghum converted to metric units and including the preplant irrigation:

$$y = -927 + 29.71\,x - 0.0259\,x^2 \qquad (62)$$

where y = grain yield in kilograms per hectare, and

x = total seasonal irrigation water, in mm,

the point of maximum profit is where:

$$\frac{\partial y}{\partial x} = 29.71 - 0.0518\,x = 4.17 \qquad (63)$$

Therefore, x = 493 mm. To this amount must be added the effective rainfall plus the available soil moisture prior to irrigation. Unfortunately, neither of these values are known. However, an average of 246 mm of rain fell between the 23rd of May 23rd September during the years from which the production function was obtained, and it would appear reasonable to assume, therefore, that at least 650 mm of water was available to the crop. Although this estimate is somewhat crude, it does indicate that the amount of water available to the crop was more than the amount necessary to insure maximum possible yield, according to figures given by Doorenbos and Pruitt (1975).

An argument might be advanced that there is nothing to stop the price of water from increasing, thereby increasing PR and hence lowering the optimal depth of water application. This is true, of course, but the key point is that the price of water can only rise a small amount without a rise in the price received for the crop before irrigation becomes uneconomical. Irrigation farmers, like other farmers, are operating on a sufficiently slender margin that the price ratio can increase very little without irrigation becoming uneconomical. If the price of water is increased, the value of the crop must increase. Water that is currently highly priced is used to irrigate highly valued crops. The price ratio, therefore, stays relatively constant. Even if it were to vary by a factor of say two or three, which allows generous latitude in the argument, it is still sufficiently low that it will always be tangential to the production function at high values of x.

For example, if the price of supplying the irrigation water increased threefold to \$0.75 per ha-mm (\$7.50 per acre-inch) the optimal depth of water application would be calculated from:

$$29.71 - 0.0518\,x = \frac{0.75}{0.08 - 0.02} \quad \ldots\ldots\ldots\ldots \quad (64)$$

$$= 12.5 \text{ kg per ha-mm}$$

Therefore, $x = 332$ mm

With only this amount of irrigation water applied, more of the seasonal rainfall would be expected to be effective. A crude estimate indicates that the total water available to the crop would be well over 500 mm plus the available soil moisture prior to irrigation. In this case, the price ratio is three times the value originally computed and yet sufficient water should still be supplied to allow the crop to receive very close to a full water supply. Obviously, though, supplying only 330 mm of water and still obtaining a high yield requires the application of novel management practices, to be discussed in the next section.

Therefore, by using current prices and a production function obtained from research plots, the conclusion is drawn that in the case where the area of land to be irrigated is fixed and sufficient water is available for total irrigation, the optimal irrigation policy is to supply close to the full water needs of the crop. Although the price of sorghum used in this analysis has been lower in past years, these were depressed prices and did not reflect the costs of production. Hence, the PR used is felt to be representative. Raising it threefold did not greatly alter the general result.

The other parameter in the analysis, the slope of the production function, bears closer inspection. The quadratic expression fitted to the four data points by Shipley (1977), as shown in Figure 42, can be seen to be actually flatter than would be a best fit curve. The quadratic expression is tangential to a line drawn with a gradient of the price ratio (4.17) when $x = 493$ mm. (The price ratio line is drawn clear of the functions for clarity.) Drawing a curve through the four data points would require that the curve be extended beyond the data to be tangential to the price ratio. That is, the quadratic expression actually gives a lower value of x_{opt} than the true function.

Alternatively, the four data points could be fitted with the power function,

$$y = 195\,x^{0.5867} \quad (r^2 = 0.985) \quad \ldots\ldots\ldots\ldots \quad (65)$$

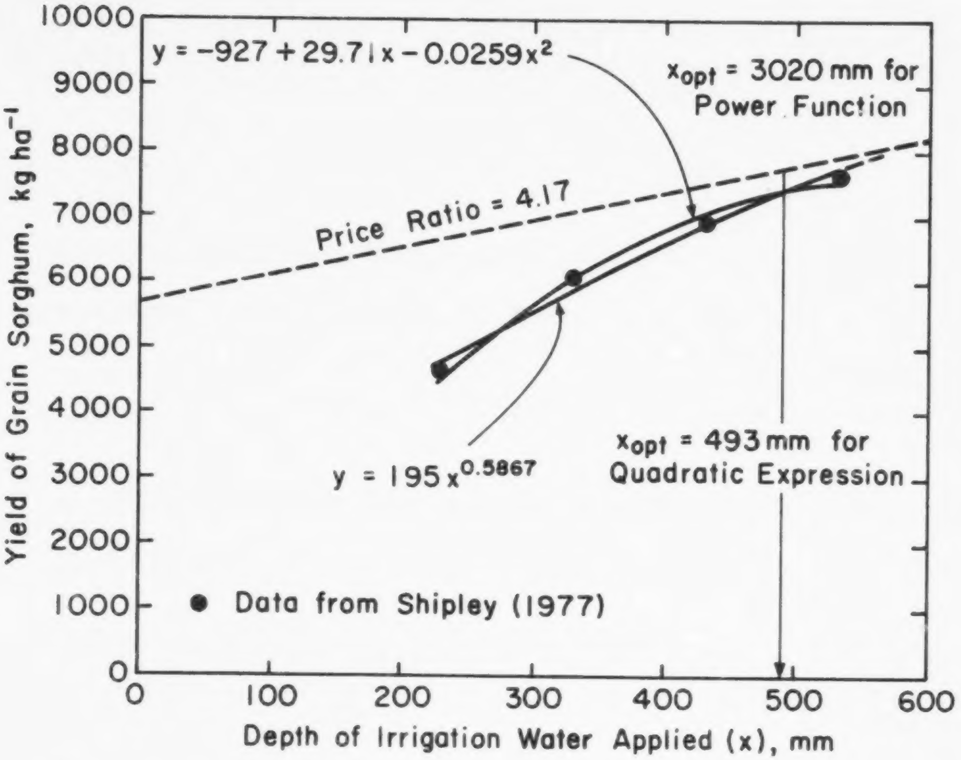


Figure 42. Influence of production function slope on optimal depth of irrigation application.

also shown in Figure 42. In this case, $dy/dx = PR$ when $x = 3020$ mm. Admittedly, the power function may not be a good expression to use over a wide range of data because it must pass through the origin. However, over the range of the four data points to which Shipley (1977) fitted the quadratic expression, it fits equally as well. The point that the power function and the preceding paragraph illustrates is that using a mathematical expression in the analysis is far from a guarantee that the correct value of x_{opt} will be obtained. It also illustrates the vast difference in the values obtained for x_{opt} for small changes in the shape of the function. This further detracts from the value of using specific yield versus applied water functions for determination of the optimal irrigation policy. Nonetheless, by observing that the gradient of the price ratio remains relatively low, and by observing the general shape of the yield versus applied water function, it may be stated that the optimal irrigation policy is to make available to the crop close to its full water requirements.

Case (I): In the case where the volume of water is fixed and the land area is not limited, the objective is to maximize profit over the total available land area, rather than profit per unit area as above. In this case, the expression for net revenue (P) is:

$$P = v_c y\, A_I - C_w - C \quad . . . . (66)$$

where C_w = cost of water (constant for a given method)

and C = the cost of operations other than those associated with irrigating:

$$\text{i.e., } C = (k + v_j y)\, A_I \quad . . . . (67)$$

and all of the other terms have been defined earlier. Therefore,

$$P = (v_c - v_j) y A_I - k A_I - C_w \quad . . . . (68)$$

In the previous case, the cost function was directly proportional to the depth of water applied (x) and hence could be plotted as a straight line. In this case, the cost function is a function of A_I,

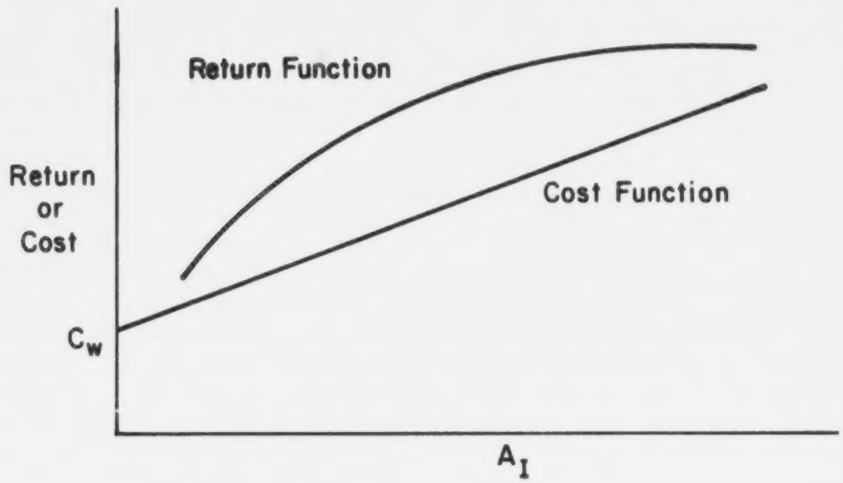
$$\text{i.e., Cost} = kA_I + C_w \quad . . . . (69)$$

$$\text{and Return} = (v_c - v_j)\, yA_I, \quad . . . . (70)$$

where A_I is inversely proportional to x as was seen in Equation 32.

$$\text{i.e., } A_I = \frac{Q}{x}$$

and x is a curvilinear function of y. Therefore, the cost function is also curvilinear when plotted against x, but linear when plotted against A_I. This may be shown graphically as:



The optimal land area to irrigate may be obtained by setting $\partial P/\partial A_I = 0$ in Equation 68.

$$\text{i.e.,}\ (v_c - v_j)y + (v_c - v_j)\frac{\partial y}{\partial A_I}A_I - k = 0 \qquad (71)$$

which may be readily manipulated to show that the optimal land area is obtained where marginal revenue equals marginal costs, or, by collecting terms may be expressed as:

$$\left(\frac{\partial y}{\partial A_I}A_I + y\right)(v_c - v_j) - k = 0 \qquad (72)$$

That is, as the return is increased by expanding irrigation to an additional unit of area, because the total quantity of water is fixed, yield on the remaining area must decline. The optimal area of irrigation is where the two factors combine for the greatest return.

Substituting $A_I = \frac{Q}{x}$

the "optimizing equation" may be expressed as:

$$\left(\frac{\partial y}{\partial x}x - y\right)(v_c - v_j) + k = 0 \qquad (73)$$

A given production function in terms of x and y and given cost coefficients may be substituted in this equation and solved for x, the optimal depth of irrigation water to apply. However, as pointed out earlier, such production functions are far from unique (or readily available) and more general results would be far more practical.

To incorporate the general case, a range of production functions is shown on Figure 43. Curves 1 and 2 have been obtained from the experimental data as plotted in Figure 38, while Curves 3 and 4 have been drawn arbitrarily to represent production functions more typical of field conditions. All curves have been plotted on a common abscissa, so that Curves 1 and 2 are no longer tangential at lower values of x. Considering x as the depth of water applied, Curve 1, originally being the plot of yield versus ET, represents a production function at 100 percent irrigation application efficiency. The seasonal irrigation application efficiency for the regime represented by Curve 2 is 82 percent, with 71 percent for Curve 3 and 48 percent for Curve 4.

To more readily understand the effect of different depths of water application on net revenue,

$$P = \text{Return} - \text{Costs} \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (74)$$

the expressions for return and costs may be plotted against x, the depth of water applied. This is shown on Figure 44 in which there is one cost function and four return functions corresponding to the four yield functions of Figure 43. The net revenue is the vertical difference between the respective return function and the cost function. Typical costs and prices have been used in plotting the curves, but this is not particularly significant as these will only affect the relative position of the return functions to the cost function and will not change the shape of either. Similarly, fixed overheads have been ignored, as these will have just the same effect. Also, for simplicity, the price of water has been taken as constant per unit volume. Breaking the total cost of watering into component parts, as done in a subsection above, only has the same effect of changing the relative position of the cost function.

The point of maximum net revenue is where the return and cost functions are separated by the greatest distance, i.e., where the curves have the same slope. This point is circled on the four return functions. The corresponding value read on the abscissa is the optimal depth of water to apply. Referring back to Figure 43, for Curve 1, this can be seen to be the amount corresponding to Y_{max}, as derived in the previous subsection. The other regimes have optimal depths of water application lower

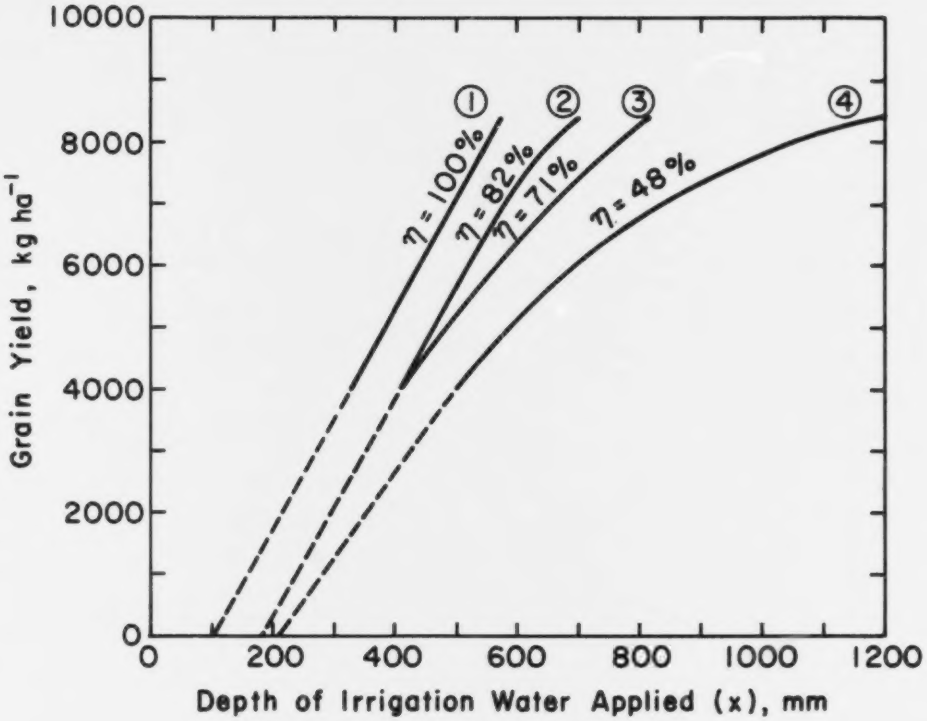


Figure 43. Production functions for corn at different irrigation application efficiencies.

than values corresponding to Y_{max}, although for the regimes corresponding to Curves 2 and 3 it is not greatly less (91 and 86 percent of x_{max}, respectively). For Curve 4, it is considerably less, with $x_{opt} = 0.58\ x_{max}$. (x_{opt} = 700 mm and x_{max} = 1200 mm). (For comparative purposes, it may be noted that in the case where water is not limited with respect to land area, Case (II), using a typical price ratio of 4 kg per ha-mm applied to Curve 4 gives $x_{opt} = 0.85\ x_{max}$.)

In general, then, it may be stated that while the optimal policy in a water abundant area is to apply close to that amount of water giving maximum yield, in a water-short area this is not true *if irrigation application efficiencies are low.* If efficiencies are high, it will be true. Although these results would appear quite reasonable by intuition, the fact that they have always been a point of controversy has required this proof.

In Case (II), the optimal depth of irrigation water to apply depended on the production function and on both the prices received for and the costs associated with producing the crop.

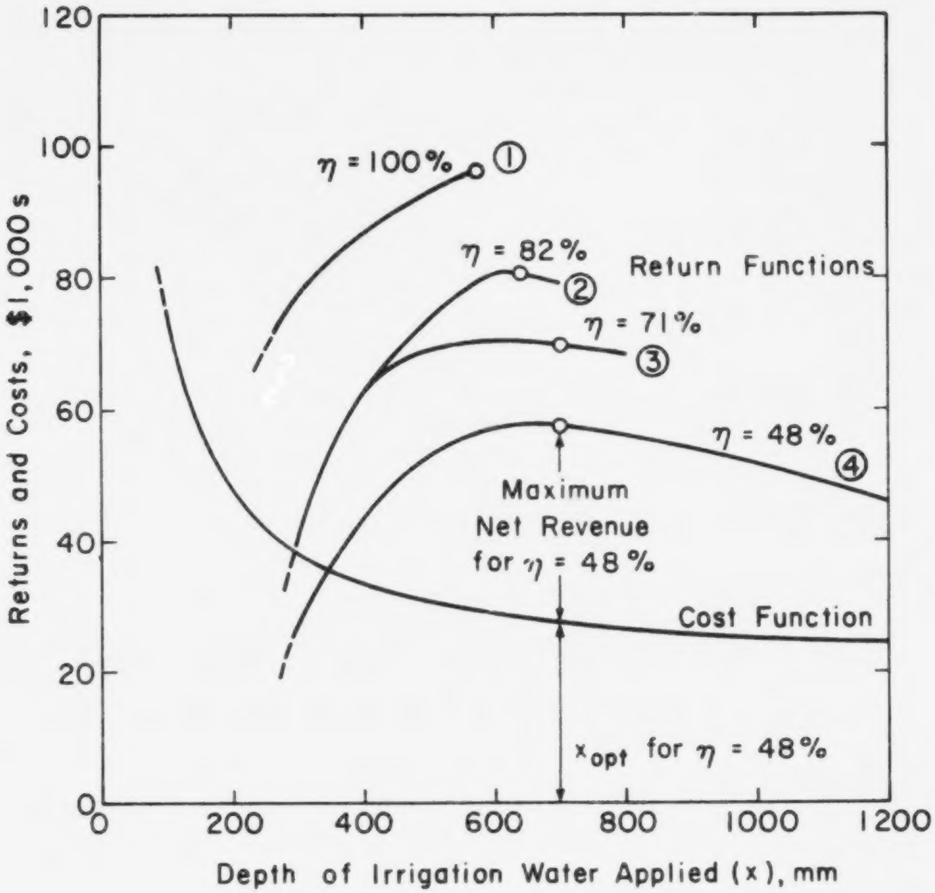


Figure 44. Variation in returns and costs with depth of irrigation water applied.

In Case (I), the optimal depth of irrigation water to apply depends solely on the shape of the production function. The effect of this shape may be readily demonstrated by referring to Figure 44. If the irrigator follows a practice resulting in a production function the same as Curve 4 in Figure 43, a maximum net revenue of $30,000 may be scaled from Figure 44. A different practice resulting in a production function the same as Curve 2 would result in a maximum net revenue of $52,000 or a 73 percent increase. As pointed out earlier, fixed overheads have been deleted for simplicity and as these would have the effect of raising the cost function, the actual effect of increasing water application efficiency would be to increase the net revenue an even greater percentage than calculated.

With costs and production functions available and return functions derived from them as shown in Figure 44, the detrimental effect of low irrigation efficiencies may be readily evaluated. The losses in revenue due to poor irrigation practices are startlingly apparent. In most cases where water is in short supply, the irrigator will endeavor to improve practices so that little water is wasted. With relatively high efficiency so attained, the correct policy is then to apply sufficient water so that close to maximum yield is obtained.

If the irrigation system is such that high efficiencies are not possible and capital is not available for improvement, the optimal depth of water to apply is significantly less than the depth corresponding to Y_{max} and could be obtained from a plot such as shown in Figure 44 or mathematically if a reliable expression for the production function were available. Unfortunately, however, such information is generally not available and, as pointed out earlier, susceptible to giving misleading results. Notwithstanding, a significant general conclusion may be drawn. That is, contrary to those who advocate spreading the available water over as large an area as possible (subject to applying the minimum depth that is practical or economical), the optimal depth to apply is similar to that under more efficient regimes and certainly greater than that which would supply the ET requirements of the crop if none were wasted. Furthermore, it is safer to err on the side of applying a greater depth of water than on the side of applying less, as the return and cost functions in Figure 44 converge far more slowly on the right hand side of the optimal depth than on the left hand side.

POLICY FOR SUPPLEMENTAL IRRIGATION

Consideration will now be given to the case where rainfed agriculture is a feasible enterprise. In this case, a greater area may be farmed than that for which an irrigation water supply is available. This case differs from the earlier consideration in that this additional area may be farmed under dryland conditions, whereas in the discussion prior to this, no cropping was feasible without irrigation.

The objective now becomes to:

$$\text{maximize } P = (O_I - I_I)A_I + (O_D - I_D)A_D. \quad . \; . \; . \; . \; . \; . \; (75)$$

subject to $A = A_I + A_D$

$x \leq x_{max}$

and $Q = \text{constant}$

where P is the profit from the total enterprise, and O_I, I_I and A_I have been defined earlier as the outputs, inputs and area, respectively, associated with irrigation, and O_D, I_D and A_D are the dryland counterparts. The irrigated area plus the dryland area must be added to give the total farmed area, A, which is constant.

As before, $O_I = v_c y$ (Eq. 34),

$$\text{and } I_I = a_j + v_j y + \frac{b_j}{A_I} \quad \ldots\ldots\ldots\ldots\ldots \quad (76)$$

Also, the profit per unit area from the dryland area (p_D) is given by:

$$p_D = O_D - I_D, \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (77)$$

which in the analysis is a constant, being dependent on the weather.

$$\text{Therefore, } P = v_c y A_I - a_j A_I - v_j y A_I - b_j + p_D A_D. \quad \ldots\ldots \quad (78)$$

$$= (v_c - v_j) y A_I - a_j A_I - b_j + p_D A - p_D A_I \quad \ldots\ldots \quad (79)$$

However, as a_j, b_j, p_D and A are constants,

$$P = (v_c - v_j) y A_I - k A_I - C \quad \ldots\ldots\ldots\ldots\ldots \quad (80)$$

$$\text{where} \quad k = a_j + p_D. \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (81)$$

$$\text{and} \quad C = b_j - p_D A \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (82)$$

Equation 77 will be recognized as being identical in form to Equation 65 and may be plotted in the same manner as the functions shown on Figure 44, which were for the case where cropping was totally dependent on irrigation. The only difference is that now the cost function, as represented by Equation 66 will be lowered by an amount, p_D, representing the increased profit due to dryland farming. To be more strictly correct, Equation 77 should be expressed as:

$$P = [(v_c - v_j) y + p_D] A_I - a_j A_I - C, \quad \ldots\ldots \quad (83)$$

$$\text{where Return} = [(v_c - v_j)y + p_D]\,A_I \;, \qquad (84)$$

$$\text{and} \quad \text{Cost} = a_j A_I + C \qquad (85)$$

If returns and costs are plotted against x, the return functions will increase by a constant amount, p_D, compared to those shown in Figure 44. Either way the relative shapes of all the functions remain unchanged, only the relative positions of the return functions to the cost function changes. The correct irrigation policy, therefore, is to supply the irrigated crop with exactly the same depth of water as calculated in the above subsection. Now, however, some of this water is supplied by precipitation during the growing season. The amount of effective rainfall to be relied upon to satisfy some part of the crop water requirements could be obtained from a statistical analysis of rainfall records. The irrigation water so saved will allow the irrigated area to be extended so that the total area receives the depth of water from both rainfall and irrigation calculated to be optimal in the above subsection. That is, having identified x_{opt}, which will be close to x_{max} for highly efficient irrigation, and with x_{opt} now including a depth of rainfall, R,

$$A_I = \frac{Q}{x_{opt} - R} \qquad (86)$$

MULTIPLE CROP DECISION

The preceding endeavors to find the optimal depth of seasonal water application have been limited to the case of a single crop. In an irrigated area, be it a farm or a district, a variety of crops usually are grown. The results may now be extended to the multiple crop case.

If no constraints applied, the optimal policy would be to plant the irrigated area with the most profitable crop and supply a seasonal irrigation requirement of x_{opt}. For Case (I), this amount would determine the command area. For Case (II), x_{opt} would determine the required water supply.

However, a number of constraints may apply to the problem. One, which in many cases will defy a completely rational analysis, may be termed a "cognitive constraint". This refers to the unwillingness of an irrigator to confine his activities to one crop. A number of reasons attend this unwillingness, including the very real necessity to rotate crops on a given land area, plus the overriding concern to deploy the inherent risk of farming. Although the most profitable crop may have been determined from conditions prevailing at the time of planting, conditions at the time of harvest may result in a different ranking. This factor becomes particularly relevant when considering, for example, perennial or orchard crops versus annual crops. Other reasons for growing additional crops may include constraints on the flow rate of the water supply, requiring times of peak water supply to be staggered; on labor, requiring a staggering of periods of labor intensive activity; and on capital, requiring the use of existing equipment. In short, the irrigator may be reluctant or unable to commit more than a certain proportion of his irrigable land to any one crop. While the existing or predicted economic conditions will allow the most profitable crop to be selected, the cognitive constraint and the other constraints will often result in a number of crops being planted. The objective is to determine the optimal depth of irrigation water to apply to each crop.

As in the single crop case, the objective in irrigating a number of crops will be to maximize the net return from the irrigation enterprise. The profitability of each crop must first be determined. This profitability could be in terms of per unit of land area or per unit depth of water.

In Case (I), where water is limited relative to the land area, a crop having the highest return per unit of land may or may not give the highest return per unit of water. In fact, two crops could give the same maximum net return per unit of land, but one may have a higher water requirement than the other. This would indicate that the higher profitability would be associated with the crop giving the highest return per unit of water, as the land area may be extended while the profitability per unit land area remains almost the same as for the other crop. While additional costs are associated with extending the land area, these costs generally are lower per unit area than for the original area, so that profit is actually higher.

In Case (II), the land area is fixed and hence the most profitable crop is that which returns the highest net revenue per unit of land. This may not necessarily be the crop which gives the highest return per unit of water. The cost of watering must be included in the computation of net revenue. Although one crop could have a higher gross return than another, it is possible that with a higher water requirement the net revenue could be lower.

The optimal depth of water to apply to each crop within a multiple crop enterprise may be determined according to the criteria developed in the above subsection for a single crop. This will be based on profitability per unit depth of water for Case (I) and profitability per unit of land for Case (II).

The relative area of each crop to be grown will be determined by the irrigator operating within the constraints outlined above. These areas could theoretically be determined by linear programming, or other techniques, although the physical and cognitive constraints often allow the solution to be obtained by inspection. The purpose here is not to describe a method whereby the optimal crop mix might be obtained, but rather, to determine whether x_{opt} determined for the single crop case is the optimal depth of water to apply to each crop when more than one crop is grown.

Where adequate water is available to supply at least x_{opt}, calculated from the single crop case, to each crop, the optimal depth for each crop in a mix of crops may be readily deduced. Applying a depth greater than x_{opt} increases costs while decreasing returns and is obviously of no benefit. Reducing the depth of water applied to one crop would be of no advantage to any other crop, as adequate water is available, although it would reduce costs. However, as these costs have been taken into account in determining x_{opt}, the profit maximizing policy remains to apply the individual x_{opt} to each crop.

If the available water supply is inadequate to provide x_{opt} to the selected area of each crop, a decision is required to determine whether the seasonal depth of water supplied to each crop should be reduced, whether the area of the least profitable crop (per unit depth of water) should be reduced, or whether the area of all crops should be reduced on a proportional basis. The solution may be deduced from Figure 45, where net revenue (returns minus costs) has been plotted against the depth of applied water. The relationship is shown for three different crops, reflecting different responses to water and different returns and costs.

If the seasonal depth of water applied to each crop were reduced below x_{opt}, the optimal relative area of each crop would be where the marginal net revenue is the same for each crop, i.e., where the functions have the same slope. Points (a) in Figure 45, for example, correspond to depth of applied water where marginal net revenues are equal. If

$$x_{1a}A_1 + x_{2a}A_2 + x_{3a}A_3 \equiv Q. \quad . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \quad (87)$$

where the x's are defined on Figure 45, the A's are the areas selected for each of the three crops being considered and Q is the total volume of available water, then the selected areas of each crop are in the optimal relative proportions for the reduced depth of application.

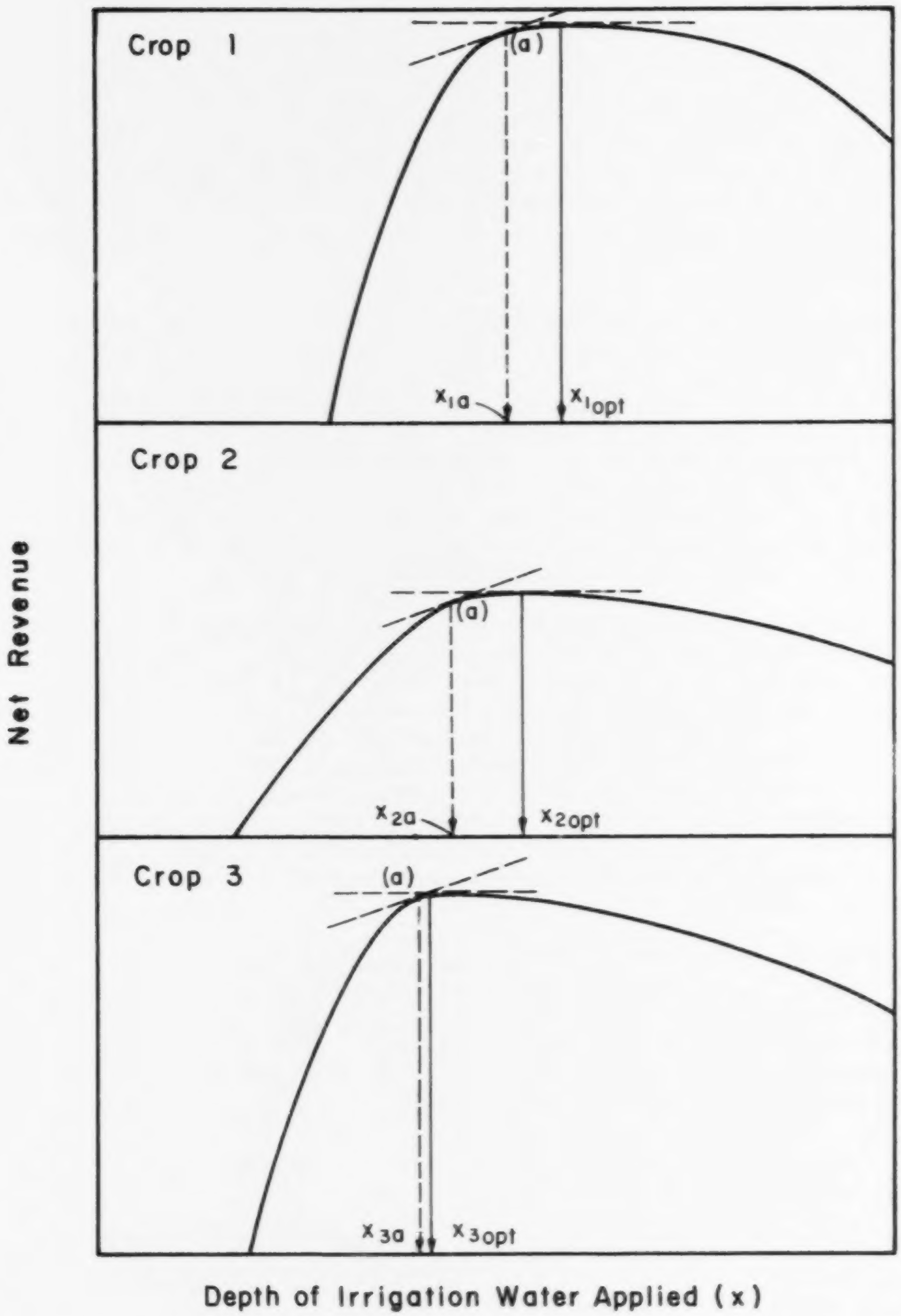


Figure 45. Determining the optimal depth of irrigation water to apply to each crop in a multiple crop enterprise.

The net revenue for any one of the crops may be increased by reducing the area of that crop until the depth of applied water is x_{opt}, i.e., to where the marginal net revenue per unit of water is zero. To maintain an optimal crop mix, the areas of all the other crops should be adjusted so that marginal net revenue is again equal, i.e., all crops should be supplied with x_{opt}. At this point, it will be noted that the net revenue from each crop is maximized and net revenue from the total enterprise is also maximized. The optimal policy, therefore, is to apply a depth of water to each crop in the crop mix calculated to be optimal if only one crop were being grown.

With the earlier, less profitable alternative, where each crop was supplied with less than x_{opt} (point (a) on the three curves of Figure 45), the area of each crop could be determined from Equation 84 if sufficient constraints were applied to the areas. The x's and Q were known. Similarly, with x_{opt} applied to each crop, the area of each may be computed. The areas corresponding to x_a and those corresponding to x_{opt} would not be in the same relative proportion. For example, the area of Crop 2 would be reduced far more than the area of Crop 3, as the ratio $x_{2a}:x_{2opt}$ is far smaller than $x_{3a}:x_{3opt}$.

Although it was stated earlier that the objective here was not to describe a method whereby the optimal crop mix might be obtained, it can be seen, in fact, that the methodology described is appropriate for solving that problem. Knowing that each crop should be supplied with x_{opt} allows the relative area of each crop to be determined if adequate constraints can be formulated. The pertinent result here, however, is that irrespective of the water supply situation, the profit maximizing policy is to apply the same depth of water to each crop of a multiple crop enterprise as would be applied if each crop were grown separately.

SECTION 11

IMPACT OF CROP PRODUCTION FUNCTIONS UPON WATER MANAGEMENT PRACTICES

The adoption of management practices which lead to increased yield per unit of water applied (called hereafter "water production efficiency" for the lack of a generally accepted term) is of benefit regardless of the water supply situation. In the case where water is limited relative to the available land area, increasing the water production efficiency allows a larger area to be irrigated with the given quantity of water. Profits may thereby be increased. In the case where land is limited relative to water availability, increasing production efficiency reduces the amount of water which must be applied, thereby reducing costs. Unfortunately, in this case it is often found that "water is cheaper than labor," with many farmers finding the cost of managing water to achieve high efficiency unjustified where the price of water is low. This is also true to some extent even where water is limited, if the price of water is sufficiently low.

Many practices may be adopted, however, which lead to an increase in the production efficiency without a substantial increase in costs. These novel management practices may be divided into two categories: those that minimize water losses and those that increase water use efficiency. In some cases, these categories overlap.

MINIMIZING LOSSES

Loss of water from the farm irrigation water supply may occur in both conveyance and application. Losses in the former are generally due to seepage, while the latter may consist of surface runoff, deep percolation or evaporation losses. Application efficiency was defined earlier as the ratio of the amount of water stored in the root zone for use by the crop to the amount delivered to the field and hence is the ratio of ET to ET plus these losses in application. Reducing the losses is tantamount to increasing the water application efficiency.

If the water supply is limited relative to the available land area, a number of managment practices may be adopted which make the most of the limited water supply. During the early development of the crop, only light irrigations are required. The ultimate root zone may then be brought close to field capacity with subsequent irrigations to ensure that during any later inadvertent water shortage, the crop may expand its root system to its fullest capacity. Apart from buffering the effect on yield of possible soil moisture shortages, the deeper root zone makes efficient irrigation easier to achieve and allows the crop to take better advantage of heavy rains. If the irrigation water supply is from on-farm storage, applying the water early in the season for storage in the root-zone reduces later evaporation from the reservoir as well as providing additional storage capacity in the reservoir. In this way losses from the water supply are reduced.

In an area where rainfall may make a substantial contribution to the crop water supply, sufficient water should be supplied during irrigation to bring the root-zone to a moisture level less than field capacity. This may be achieved, for example, by alternative furrow watering or by replacing just a fraction of the soil-moisture deficit when sprinkler irrigating. Maximum use of rainfall may thereby be achieved and the loss of nutrients due to deep percolation reduced. The deficit allowed to remain in root-zone soil-moisture storage would have to be based on historical rainfall records. An exception may be necessary during the period of peak crop water use when the root-zone would need to be brought to near field capacity unless rainfall is assured with a high degree of reliability.

To reduce evaporation losses, irrigations should be as infrequent as possible within the limits set by the above requirements and the type of crop. This is particularly true in the early stages of growth when the crop canopy shades only a small fraction of the ground surface. By allowing the soil surface to dry out between waterings, evaporation from the soil surface may be considerably reduced. Irrigating at night will also lower the evaporation and wind drift losses when irrigating with sprinklers. These two measures combined will allow considerable water savings to be effected.

With many crops, late season irrigation has been shown to be nonbeneficial or even detrimental to yields. This was shown to be true for both corn and wheat in the experiment conducted in this research effort. Water can thus be saved if these waterings are avoided, with this water being used to extend the irrigated area or to avoid deficits in earlier growth stages. Ending the season with the root-zone at a lower moisture level allows full advantage to be taken of interseasonal precipitation. In addition, avoiding or reducing the late season irrigations may reduce nitrogen losses by deep percolation from either the late irrigations or from the interseasonal precipitation. The usual nitrogen fertilizer rates result in fairly significant residual nitrogen levels at the end of the season, with this nitrogen to be subsequently "scavenged" by future crops if not leached from the soil profile.

From the results of the experiment with corn reported in Section 8, it may be seen that the last four irrigations had a detrimental effect on grain yield, as well as reducing the seasonal water application efficiency from 82 to 64 percent. Figure 34 indicated the disastrous effects on profitability of these late season waterings. Fortunately, it is easier to avoid this cause of inefficiency (by failure to irrigate) than it is to promote it.

If the area of irrigated land is limited relative to the available water supply, there is seldom an expressed concern to improve application efficiencies unless the cost of the water is comparatively high. However, improving the water application efficiency in this case has a number of benefits, some of which are often overlooked.

A number of researchers have shown that overirrigation can be severely detrimental to yields. If waterlogged conditions prevail during flowering, the oxygen diffusion rate in the soil can be so low that basic metabolic activities of the roots are inhibited and consequently, grain yield is severely depressed (Downey, 1972). In this case, improved irrigation efficiency could be of marked benefit in terms of increased returns. Water percolating below the root-zone carries with it some of the soluble nutrients present in the soil profile. The leaching of nutrients from the root-zone represents a cost in terms of reduced yields and the replacement cost of the nutrients.

In some areas of abundant water supplies, excessive runoff accompanies deep percolation and where the soils are erosive or the slopes relatively steep, extensive loss of topsoil occurs. Many of the costs associated with this topsoil loss, if perceived at all, are viewed as externalities, with the direct costs being borne by downstream water users. However, as the downstream end of an irrigation furrow is the point of lowest discharge, and usually of lowest velocity, it is often the point of least erosion. Much of the erosion occurs higher in the field, with the sediment deposited further downstream in the furrow. Hence, the internal cost to the farmer, although not always perceived, may be high.

Some of the costs associated with low water application efficiencies are readily apparent, although, as noted above, in some cases there may be a tendency to balance these costs against the additional costs necessary to achieve higher efficiency. This may be the case particularly with the water charges or the cost of pumping water. In some cases, however, even the cost of additional labor is expended unnecessarily, where additional irrigations are applied when not needed. Late irrigations, apart from the possible losses associated with yield reduction, may also expose the mature crop to a higher risk of storm damage if the resulting wet soil delays harvest.

INCREASING WATER USE EFFICIENCY

Water use efficiency has been defined by Viets (1962) as "the weight of dry matter or marketable crop produced per unit volume of water used in evapotranspiration (ET)." It therefore differs from water production efficiency defined above by having ET in the denominator, rather than applied water. Metric units are often preferable. If both the yield and ET are expressed in units of mass, then water use efficiency becomes a true ratio. In mass units, water use efficiency is similar to the term "efficiency of transpiration," first attributed to L. A. Ivanov in 1913. Efficiency of transpiration was defined as the grams of dry matter produced per kilogram of water transpired (Viets, 1962).

Improving water use efficiency can be accomplished by either increasing the yield or decreasing the ET. As yield is a linear function of ET under conditions of optimal irrigation timing and quantities, with a positive intercept on the ET axis, the maximum water use efficiency occurs at the ET corresponding to maximum yield. For this quantity of ET, or any other ET, water use efficiency can only be increased by increasing yield. Yield improvements can be divided into two categories: those affected by agronomic and plant genetic factors and those affected by management factors.

The agronomic and genetic factors fall outside of the scope of this work and shall only be listed briefly. These include species adaptation (variety or hybrid), plant breeding, plant shape and form, planting patterns (row spacing and planting rate), planting date, seed quality, weed control, control of disease and insect pests, and fertilization (Pendleton, 1966).

Management factors are those which are concerned with achieving maximum yield for the given amount of ET, whether or not maximum benefit has been taken of the agronomic and genetic factors. Obviously, the two are most effective in conjunction.

Where water is cheap and abundant, the overall management objective is to prevent water deficits at any stage of growth in order to achieve maximum yields. In some cases, due perhaps to maintenance becoming necessary in mid-season, deficits which could not be foreseen at the time of planting become inevitable. In the case where water is limited relative to the available land area, and where the water application efficiency is low, deficits will be necessary according to the optimal irrigation policy derived in Section 10. In either case, deficits should be sequenced to cause the minimum reduction in yield if at all possible. Research results, such as those presented for corn and wheat in Section 8 and more comprehensively elsewhere (i.e., Salter and Goode, 1967), will show those periods in which deficits should be avoided. An understanding of the effects of the timing of water deficits on the crop production function and the subsequent effect on net revenue will provide a powerful tool for profit maximization.

Many researchers and farmers have demonstrated the necessity of coinciding the maximum water demand of the crop, determined by its physiological requirements, with the time of maximum atmospheric evaporative demand. This is often expressed in terms of date of sowing. Sowing corn, for example, as early as climatic conditions will allow ensures that the full crop canopy is developed by the time of maximum evaporative demand and results in higher yields provided that water is not limiting. This practice is mentioned under the agronomic factors listed above. If, however, there is a flow rate constraint on the available water supply, or a labor constraint, it may not be possible to meet the peak consumptive demand even though the volume of available water is sufficient for the crop's seasonal needs. In this case, a crop mix may be selected in which critical growth stages do not temporally coincide. With a single crop, planting dates may be spread to stagger the time of occurrence of the critical growth stage. Depending on the climate, the period of peak evaporative demand may spread over a month or more. The length of this spread will determine the reasonable staggering of the planting dates.

With a constrained flow rate, the situation becomes analogous to the supplemental irrigation situation analyzed in Section 10, where it was shown that the available irrigation water should be confined to an area on which a seasonal depth of water, including precipitation, equal to or greater than the crop ET requirements should be applied. With the constrained flow rate, during the period of peak demand, irrigation should be confined to an area which allows this criterion to be met, with the remaining area irrigated when the demands are lower. Beginning the season with the root-zone storage at or near field capacity, or at least ensuring that it is to the desired moisture level at the beginning of the period of peak demand, will be of considerable benefit in allowing time to adequately water the irrigated area within the constraints of flow rate or labor availability. Consideration should also be given to other methods of application, such as sprinkler irrigation or trickle irrigation, which are better able to utilize small flow rates than many surface methods.

BEST MANAGEMENT PRACTICES FOR GRAND VALLEY

Much of the research results reported herein have general applicability to irrigated agriculture. In this final subsection of this report, the authors will attempt to summarize the implications of this research in implementing a salinity control program in Grand Valley. The results of this particular research effort will be combined with the other research efforts funded by EPA in Grand Valley in preparing the culminating report, "'Best Management Practices' for Salinity Control in Grand Valley."

Since the Grand Valley has a limited irrigable acreage, but a more than adequate irrigation water supply, it would be a Case (II) area as defined in this report. The Valley contains predominately heavy soils, which strongly influence the present irrigation practices. Another consideration is that the mean annual precipitation of 210 mm occurs mostly during the winter months, with the summer rainfall occurring mostly as the result of thunderstorms, particularly in July and August.

The most important and far-reaching result from this research is confirming very recent reports (Stewart et al., 1976; Shalhevet et al., 1976; Consortium for International Development, 1976) that a linear relationship does exist between crop yield and evapotranspiration. Previous research (Skogerboe et al., 1974) in Grand Valley has shown the necessity to reduce deep percolation losses from irrigated croplands to substantially reduce the salt pickup and consequently the salt load in the Colorado River. A companion report, "Evaluation of Irrigation Methods for Salinity Control in Grand Valley," will address the importance of advanced irrigation methods (i.e., sprinkler irrigation or trickle irrigation) for substantially reducing deep percolation losses, which is achieved by attaining high irrigation application efficiencies. By substantiating the linear relationship between crop yield and evapotranspiration, and taking into account the physical characteristics of Grand Valley, it has been shown in this report that crop yields will be increased by attaining high irrigation application efficiencies. In a general sense, this result was intuitively known. However, there are numerous benefits in documenting this result in Grand Valley: first of all, it removes doubts by other investigators; provides some quantification of the benefits in increased crop yields to be gained by employing more efficient irrigation methods and practices; and most importantly, allows the research results and implications to be incorporated into an action salinity control program for Grand Valley.

Another highly important result from this crops research is showing that irrigation of both corn and wheat can be terminated much earlier than is commonly practiced in Grand Valley.

Again, this result was intuitively known, but there is considerable advantage in providing documentation so that this result can be incorporated into an action salinity control program. A practical recommendation for Grand Valley would be the I-I-O irrigation treatment for corn, where irrigation water is not applied during the grain filling growth stage. Although it will take some time to gain acceptance by farmers to terminate the irrigation of corn and wheat at an earlier date, there are definite advantages to farmers in reduced labor by eliminating one or two irrigations. This improved practice is independent of the irrigation method being used by each farmer.

The research by Ayars (1976) has shown that interseasonal (winter) precipitation in Grand Valley can contribute to groundwater flow in Grand Valley, and consequently, result in increased salt loads reaching the Colorado River. By terminating irrigation of corn and wheat crops earlier than is presently practiced, there will be more soil moisture storage available in the root-zone for interseasonal precipitation, thereby reducing the likelihood of winter precipitation reaching the underlying shallow groundwater aquifer.

Earlier termination of irrigation for corn and wheat (grain crops) in Grand Valley will result in less nitrogen fertilizer being lost from the root-zone. Present fertilizer practices in Grand Valley frequently result in fairly significant residual nitrogen levels in the soil profile at the end of the season. A combination of improved irrigation methods that achieve high irrigation application efficiencies and earlier termination of irrigation would result in significant increases in fertilizer use efficiency by reducing both the quantities of fertilizer applied and the amount that is leached below the root-zone.

Improved agronomic practices, such as the research results reported herein, should be incorporated into the action salinity control program to be undertaken in the Grand Valley by the Soil Conservation Service (SCS) and U.S. Bureau of Reclamation (USBR). First of all, farmers must be made aware of the benefits to be gained by such improved practices. Then, these improved agronomic practices should be made a part of the irrigation scheduling service that is to be provided under the action program.

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APPENDIX A

DAILY CLIMATIC DATA, APRIL-NOVEMBER, 1976

TABLE A-1. DAILY CLIMATIC DATA, MATCHETT FARM, 1976 (MONTH: APRIL)

Date	Temperature (°F)		Rainfall (in.)	Max.Rel. Humidity (%)	Radiation (Langleys)	Wind Run (miles)	Evaporation (in.)	Lysimeter Use (in)	
	Maximum	Minimum						North	South
1	70	33		45	Out of Order	318	.301	--	--
2	68	26		26	Out of Order	151	.263	--	--
3	70	28		31	Out of Order	169	.231	.123	.091
4	68	38		40	Out of Order	236	.241	.084	.087
5	62	39	.03	42	Out of Order	283	.180	.049	.025
6	54	27			Out of Order	196	.018	.062	.060
7	58	37		76	Out of Order	166	.162	.073	.061
8	65	32		57	Out of Order	199	.153	.071	.090
9	66	41		33	Out of Order	333	.262	.142	.108
10	69	32		40	Out of Order	196	.338	.107	.088
11	76	35		38	Out of Order	263	.276	.125	.119
12	67	44	.01		Out of Order	436	.386	.077	.068
13	62	42			Out of Order	295	.194	.090	.078
14	51	41	.04		Out of Order	208	.241	.019	.010
15	56	30		68	Out of Order	263	.003	.065	.052
16	57	35	.25	89	Out of Order	275	.212	.043	.019
17	53	33		93	Out of Order	251	-.116	.024	.002
18	50	35	.24	93	Out of Order	124	-.097	.150	.000
19	57	40		95	Out of Order	121	-.012	.174	.000
20	59	31		57	Out of Order	215	.168	.217	.000
21	69	38		48	Out of Order	242	.206	.186	.080
22	71	45		35	392*	272	.273	.181	.118
23	68	43		64	500*	262	.290	.185	.124
24	68	31		41	500*	481	.235	.174	.127
25	74	39		34	500*	542	.273	.182	.182
26	52	33		67	528*	346	.384	.224	.132
27	58	23		76	569*	134	.267	.150	.094
28	68	32		59	602*	164	.224	.164	.134
29	72	38		57	532*	271	.278	.128	.150
30	63	36		75	591*	227	.338	.084	.139

* From correlation with Agricultural Research Service data, collected nearby.

TABLE A-2. DAILY CLIMATIC DATA, MATCHETT FARM, 1976 (MONTH: MAY)

Date	Temperature (°F)		Rainfall (in.)	Max.Rel. Humidity (%)	Radiation (Langleys)	Wind Run (miles)	Evaporation (in.)	Lysimeter Use (in)	
	Maximum	Minimum						North	South
1	68	31		71	648*	188	.236	.028	.155
2	71	34		55	550*	198	.307	.183	.158
3	77	43		47	542*	160	.271	.163	.124
4	65	44	.04	50	294*	206	.301	.031	.012
5	70	41	.02	92	622*	135	.073	.207	.113
6	60	41	.26	80	131*	165	.139	.022	.000
7	66	42	.10	90	387*	153	-.116	.012	.001
8	56	43	.10	98	428*	128	-.328	.153	.004
9	68	43		94	428*	124	-.126	.131	.001
10	73	42		72	628*	214	.180	.153	.006
11	77	49		63	490*	290	.276	.136	.011
12	68	36		56	661	196	.321	.244	.132
13	78	36		60	655	126	.284	.232	.170
14	84	45		55	712	159	.227	.122	.213
15	75	44		60	622	294	.335	.079	.249
16	74	38		60	770	168	.359	.104	.225
17	80	42		66	708	110	.287	.261	.224
18	81	52		51	420	103	.318	.246	.201
19	80	55	.01	56	425	197	.232	.182	.133
20	66	41	.14	87	290	91	.139	.002	.001
21	62	50	.23	95	251	70	.128	.014	.000
22	66	42	.11	98	386	121	.030	.024	.001
23	71	41		93	630	109	.033	.050	.044
24	76	46	.11	91	393	161	.182	.113	.088
25	73	41		76	484	165	.053	.198	.146
26	76	40		80	676	101	.220	.295	.227
27	80	45		65	677	173	.243	.350	.286
28	85	51		45	672	188	.287	.430	.346
29	81	49		50	585	164	.326	.360	.288
30	70	47		66	291	185	.274	.227	.177
31	80	43		70	679	162	.220	.392	.318

* From correlation with Agricultural Research Service data, collected nearby.

TABLE A-3. DAILY CLIMATIC DATA, MATCHETT FARM, 1976 (MONTH: JUNE)

Date	Temperature (°F)		Rainfall (in.)	Relative Humidity (%)	Radiation (Langleys)	Wind Run (miles)	Evaporation (in.)	Lysimeter Use (in)	
	Maximum	Minimum						North	South
1	84	50		77	611	156	.205	.409	.325
2	87	50		80	645	224	.311	.479	.386
3	84	54		48	631	287	.310	.582	.484
4	84	52		40	657	237	.427	.547	.461
5	89	50		48	691	193	.379	.566	.464
6	84	53		49	491	333	.368	.421	.366
7	86	53		61	497	145	.259	.454	.369
8	85	53		61	522	205	.323	.466	.420
9	88	56		61	676	235	.292	.642	.565
10	88	55		43	663	402	.416	.808	.700
11	72	43		36	567	299	.562	.602	.508
12	74	43	.01	85	682	249	.352	.532	.495
13	82	47		40	376	296	.370	.692	.370
14	66	31	.01	95	703	201	.291	.534	.430
15	75	38		65	700	215	.320	.609	.559
16	86	46		49	558	278	.380	.782	.660
17	73	50	.04	85	562	186	.424	.462	.391
18	78	42		83	697	202	.220	.665	.569
19	85	49		27	778	242	.402	.769	.639
20	94	55		43	645	224	.478	.826	.813
21	93	58	Trace	59	662	307	.435	.893	.764
22	72	59	.04	84	224	207	.334	.279	.231
23	76	46		87	673	196	.334	.691	.576
24	77	43		64	718	156	.349	.645	.563
25	85	47		41	729	180	.339	.794	.689
26	87	47		62	693	165	.408	.728	.583
27	92	53		47	705	175	.430	.849	.719
28	95	54		44	727	143	.387	.830	.697
29	94	58		45	610	311	.252	.989	.846
30	88	62	.08	47	409	338	.526	.572	.572

TABLE A-4. DAILY CLIMATIC DATA, MATCHETT FARM, 1976 (MONTH: JULY)

Date	Temperature (°F)		Rainfall (in.)	Max.Rel. Humidity (%)	Radiation (Langleys)	Wind Run (miles)	Evaporation (in.)	Lysimeter Use (in)	
	Maximum	Minimum						North	South
1	87	56		85	687	188	.227	.698	.594
2	90	61		59	688	190	.343	.871	.726
3	90	51		54	726	149	.418	.816	.685
4	92	57		40	747	208	.377	.980	.839
5	94	56		45	671	151	.477	.732	.685
6	96	60		42	655	194	.393	.854	.707
7	92	68		43	488	262	.403	.737	.633
8	94	63		58	667	176	.413	.776	.640
9	96	62		51	702	235	.398	.785	.608
10	97	64		54	719	230	.461	.797	.736
11	95	60		62	633	188	.454	.677	.602
12	92	62		66	490	169	.508	.566	.411
13	88	59	.09	86	684	131	.343	.485	.413
14	91	58		60	731	173	.370	.702	.562
15	89	54		61	632	163	.363	.731	.528
16	93	58		46	696	127	.369	.695	.491
17	89	63	.03	54	578	169	.228	.623	.406
18	82	57	.09	79	407	152	.118	.404	.235
19	77	57		96	442	220	.290	.379	.212
20	85	64		84	557	146	.206	.522	.357
21	86	51		88	694	147	.316	.574	.433
22	91	55		65	692	154	.348	.505	.492
23	92	58		49	689	228	.544	.548	.556
24	90	60		53	706	127	.337	.492	.483
25	85	64		62	517	196	.336	.433	.393
26	84	61		80	420	152	.207	.271	.215
27	88	60		71	656	146	.339	.389	.351
28	92	59		56	665	133	.291	.391	.359
29	91	60		53	630	104	.253	.381	.323
30	92	60		60	684	215	.383	.333	.394
31	88	63		72	457	149	.109	.298	.260

TABLE A-5. DAILY CLIMATIC DATA, MATCHETT FARM, 1976 (MONTH: AUGUST)

Date	Temperature (°F)		Rainfall	Max.Rel. Humidity	Radiation	Wind Run	Evaporation	Lysimeter Use (in)	
	Maximum	Minimum	(in.)	(%)	(Langleys)	(miles)	(in.)	North	South
1	80	59	.11	98	410	173	.221	.135	.130
2	84	58		80	529	104	.181	.253	.228
3	78	58		67	457	402	.311	.327	.296
4	83	57		65	629	230	.338	.395	.333
5	86	50		45	668	166	.278	.358	.305
6	87	54		38	668	241	.421	.449	.355
7	84	58		41	450	304*	.275	.264	.204
8	80	56	.10	73	228	312*	.051	.264	.204
9	85	53		80	680	170*	.316	.293	.217
10	82	53		45	434	208*	.166	.269	.209
11	82	56	.11	61	544	298*	.251	.308	.203
12	87	51		75	640	174*	.294	.332	.247
13	83	55	.06	50	504	158*	.133	.243	.165
14	85	52		70	623	210*	.374	.429	.307
15	83	62		38	455	296*	.327	.384	.269
16	83	57		47	610	208*	.331	.422	.306
17	85	63	.01	52	314	160*	.136	.214	.151
18	84	55		90	573	198*	.292	.331	.236
19	84	56		61	562	200*	.254	.353	.259
20	88	56		70	619	116*	.237	.328	.248
21	90	57		67	589	124*	.242	.343	.262
22	91	59		57	391	194*	.231	.313	.233
23	87	62		74	574	154*	.260	.413	.326
24	88	52		72	574	110*	.259	.278	.198
25	91	56		68	577	134*	.320	.376	.298
26	88	61	.01	46	452	194*	.297	.361	.265
27	82	49		93	607	88*	.318	.339	.269
28	87	50		58	599	138*	.284	.363	.293
29	89	53		50	560	188*	.311	.393	.317
30	90	55		55	476	180*	.291	.368	.292
31	85	51		83	598	200*	.369	.404	.323

*Data from Walker Field Airport, corrected for height.

TABLE A-6. DAILY CLIMATIC DATA, MATCHETT FARM, 1976 (MONTH: SEPTEMBER)

Date	Temperature (°F)		Rainfall (in.)	Max.Rel. Humidity (%)	Radiation (Langleys)	Wind Run (miles)	Evaporation (in.)	Lysimeter Use (in)	
	Maximum	Minimum						North	South
1	84	49		63	572	140*	.290	.350	.276
2	88	44		58	589	126*	.270	.331	.244
3	92	52		52	629	140*	.297	.337	.243
4	93	52		45	585	116*	.293	.333	.251
5	92	55		44	515	140*	.201	.327	.242
6	72	58	.01	90	199	132*	.029		.251
7	79	52		95	524	98*	.205	.237	.178
8	79	47		81	559	128*	.274	.280	.222
9	79	48		54	467	124*	.177	.247	.182
10	71	52	.02	75	255	72*	.043	.090	.063
11	78	54	.01	80	400	142*	.088	.181	.127
12	74	59	.04	100	467	88*	.168	.192	.141
13	79	48		86	530	116*	.229	.252	.195
14	81	49		77	449	94*	.178	.247	.186
15	79	53		55	307	200*	.281	.212	.148
16	82	51		79	443	182*	.107	.262	.199
17	82	55		60	501	210*	.349	.331	.247
18	78	54		57	507	170*	.231	.281	.221
19	78	44		56	503	122*	.143		.265
20	79	48		67	504	140*	.211		
21	74	47	.01	57	319	152	.130	.258	.138
22	72	44		99	495	103	.167	.286	.143
23	74	45		86	325	103	.019	.230	.121
24	60	50	.27	98	199	16	-.139	.176	.007
25	66	49		98	273	73	.110	.142	.002
26	59	48		96	269	69	-.055	.143	.022
27	66	40		99	448	103	.145	.214	.029
28	71	38		64	463	90	.147	.223	.125
29	76	39		60	518	104	.138	.229	.119
30	76	40		69	455	100	.165	.186	.136

*Data from Walker Field Airport, corrected for height.

TABLE A-7. DAILY CLIMATIC DATA, MATCHETT FARM, 1976 (MONTH: OCTOBER)

Date	Temperature (°F)		Rainfall (in.)	Max.Rel. Humidity (%)	Radiation (Langleys)	Wind Run (miles)	Evaporation (in.)	Lysimeter Use (in)	
	Maximum	Minimum						North	South
1	80	44		59	330	95	.096	.157	.101
2	70	50	.44	63	180	136	-.400	.136	.042
3	64	40		100	335	85	.132	.124	.002
4	64	38		80	468	83	.130	.121	.004
5	64	33		82	519	72	.057	.123	.007
6	64	33		73	393	199	.176	.103	.054
7	60	30		52	375	89	.124	.094	.068
8	68	30		67	499	100	.114	.112	.085
9	70	34		68	430	68	.138	.100	.081
10	72	33		59	439	142	.164	.105	.096
11	72	41		47	297	78	.063	.087	.074
12	71	32		75	433	146	.177	.098	.094
13	71	33		70	556	138	.154	.117	.107
14	70	33		71	328	81	.144	.090	.072
15	74	33		67	422	52	.122	.134	.081
16	72	30		64	412	116	.131	.130	.081
17	71	38		61	340	143	.169	.121	.080
18	52	24		72	321	119	Frozen		.040
19	56	21		72	423	73			
20	60	23		55	416	103			
21	62	25		52	393	85			
22	61	26		76	285	78			
23	64	31		80	384	104			
24	63	33		71	363	131			
25	63	27		76	363	158			
26	52	21		82	222	186			
27	56	23		85	387	97			
28	62	23		75	387	86			
29	56	20		77	406	110			
30	61	22		73	454	117			
31	62	25		72	234	66			

TABLE A-8. DAILY CLIMATIC DATA, MATCHETT FARM, 1976 (MONTH: NOVEMBER)

Date	Temperature (°F)		Rainfall (in.)	Max.Rel. Humidity (%)	Radiation (Langleys)	Wind Run (miles)	Evaporation (in.)	Lysimeter Use (in)	
	Maximum	Minimum						North	South
1	65	27		69	368	114			
2	66	30		84	353	93			
3	66	30		74	325	117			
4	63	27		90	352	99			
5	64	27		76	387	104			
6	65	28		69	288	64			
7	65	27		66	335	82			
8	63	24		76	332	70			
9	66	25		72	332	86			
10	56	24							
11	59	22							
12	52	24							
13	46	29							
14	50	30							

APPENDIX B

TABLE B-1. MATCHETT FARM EVAPOTRANSPIRATION PARAMETERS, 1976

			Weather Data						Saturation Vapor Pressure	
Week	Modified Date	Julian Interval	T_{min} °C	T_{max} °C	T_{av} °C	Relative Humidity	R_s ly/day	u_2 mi/day	$(e°)_{T_{max}}$	$(e°)_{T_{min}}$
1	64-70	May 3-9	5.3	18.9	12.3	.787	405+	153	21.8	9.23
2	71-77	10-16	5.2	24.2	14.7	.609	648+	207	30.2	8.86
3	78-84	17-23	7.8	22.4	15.1	.780	444	103	27.1	10.6
4	85-91	24-30	7.6	25.2	16.4	.676	540	162	32.0	10.5
5	92-98	May 31-June 6	10.2	29.1	19.6	.589	629	228	40.3	12.5
6	99-105	June 7-13	10.0	27.8	18.9	.553	569	261	37.3	12.3
7	106-112	14-20	6.9	26.4	16.7	.636	663	221	34.4	9.96
8	113-119	21-27	10.2	28.4	19.3	.634	629	198	38.7	12.5
9	120-126	June 28-July 4	13.9	32.7	23.3	.534	656	218	49.4	15.9
10	127-133	July 5-11	16.6	34.9	25.8	.507	648	205	55.9	18.9
11	134-140	12-18	14.8	31.7	23.3	.646	603	155	46.7	16.8
12	141-147	19-25	14.7	30.3	22.5	.710	614	174	43.1	16.7
13	148-154	July 26-Aug. 1	15.7	31.1	23.4	.700	560	153	45.2	17.8
14	155-161	Aug. 2-8	13.3	28.4	20.8	.584	519	251*	38.7	15.5
15	162-168	9-15	12.6	28.8	20.7	.599	544	216*	39.6	14.6
16	169-175	16-22	14.2	30.2	22.2	.634	522	171*	42.9	16.2
17	176-182	23-29	12.6	30.8	21.7	.659	563	144*	44.4	14.6
18	183-189	Aug. 30-Sept. 5	10.6	31.7	21.2	.571	566	149*	46.7	12.8
19	190-196	Sept. 6-12	11.6	24.4	18.0	.821	409	112*	30.6	20.6
20	197-203	13-19	10.3	26.6	18.5	.674	463	156*	34.8	12.5
21	204-210	20-26	8.5	20.6	14.6	.859	341	93	24.3	11.1
22	211-217	Sept. 27-Oct. 3	5.3	22.2	13.8	.734	390	102	26.8	8.92
23	218-224	Oct. 4-10	0.6	18.9	9.7	.687	446	108	21.8	6.39
24	225-231	11-17	1.3	22.0	11.6	.650	398	108	26.4	6.72
25	232-238	18-24	-3.3	15.4	6.1	.683	369	99	17.5	4.79
26	239-245	25-31	-5.0	14.9	5.0	.771	351	117	17.0	4.22
27	246-252	Nov. 1-7	-2.2	18.3	8.0	.754	344	96	21.0	5.20

* Walker Field data, corrected for height of anemometer

+ From ARS readings, using $(R_s)_{CSU} = 1.569(R_s)_{ARS}^{0.915}$ $(r^2 = 0.916)$

APPENDIX C

TABLE C-1. EVAPOTRANSPIRATION PER GROWTH STAGE OF CORN

Treatment	Plot	Growth Stage*				Total
		0	I	II	III	
		(mm)				
0-0-0	20	51	165	60	27	303
	32	51	144	47	49	291
	36	51	165	44	48	308
	45	51	197	114	53	415
I-0-0	24	51	201	81	79	412
	27	51	201	111	85	448
	39	51	201	62	86	400
	43	51	201	115	85	452
0-I-0	18	51	161	224	78	514
	28	51	83	224	65	423
	37	51	135	224	51	461
	42	51	135	224	86	496
0-0-I	22	51	140	127	145	463
	25	51	101	80	174	406
	35	51	70	132	174	427
	41	51	95	74	174	414
I-I-0	21	51	201	224	102	578
	30	51	201	224	113	589
	40	51	201	224	100	576
	48	51	201	224	92	568
I-0-I	19	51	201	81	174	507
	29	51	201	87	174	513
	34	51	201	81	174	507
	46	51	201	102	174	528
0-I-I	23	51	94	191	174	510
	31	51	70	224	174	519
	33	51	105	224	174	554
	44	51	50	224	174	499
I-I-I	17	51	201	210	174	636
	26	51	201	210	174	636
	38	51	201	224	174	650
	47	51	201	215	174	641

*as defined in Figure 16

APPENDIX D

TABLE D-1. CORN YIELDS AND ET OF EACH PLOT

Treatment	Plot	Seasonal ET (mm)	Dry matter yield (kg ha^{-1})	Grain yield (kg ha^{-1})
0-0-0	20	303	6078	3660
	32	291	7178	3430
	36	308	8337	3528
	45	415	9906	5678
	Average	329	7875	4074
I-0-0	24	412	10961	4615
	27	448	10162	4433
	39	400	12405	6105
	43	452	14264	7199
	Average	428	11948	5588
0-I-0	18	514	10494	7132
	28	423	7279	5144
	37	461	13573	8881
	42	496	9541	5015
	Average	474	10222	6543
0-0-I	22	463	10850	5941
	25	406	7347	4381
	35	427	10240	5294
	41	414	6070	4582
	Average	428	8627	5050
I-I-0	21	578	12205	10957
	30	589	12018	8645
	40	576	10196	6215
	48	568	17255	7796
	Average	578	12919	8403
I-0-I	19	507	6889	5901
	29	513	10978	7943
	34	507	9350	5663
	46	528	9058	3570
	Average	514	9069	5769
0-I-I	23	510	9622	4776
	31	519	12187	8481
	33	554	11087	7917
	44	499	9947	7093
	Average	521	10711	7067
I-I-I	17	636	11620	8301
	26	636	11413	6555
	38	650	15351	10051
	47	641	15592	7544
	Average	641	13494	8113

APPENDIX E

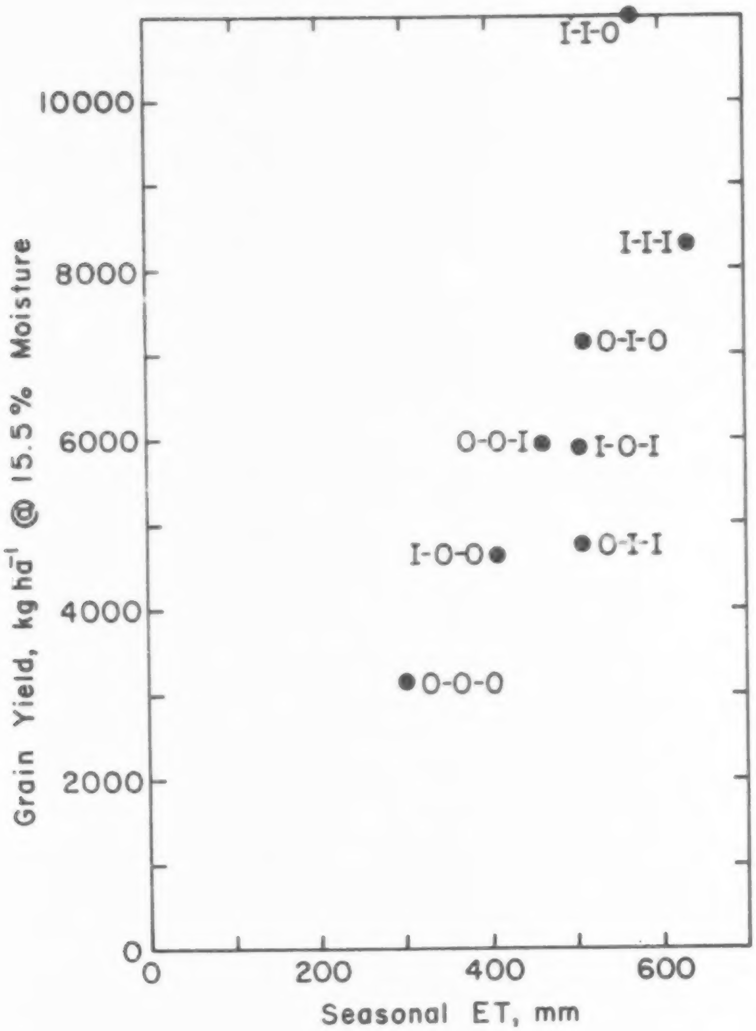

Figure E-1. Corn grain yield versus ET: Replication I.

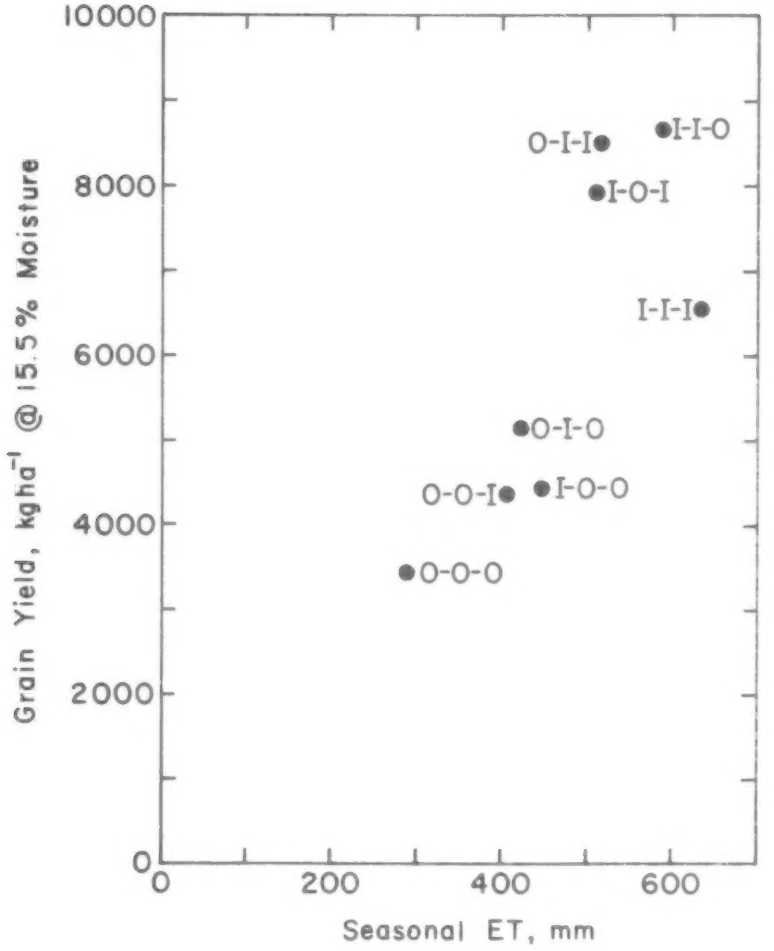

Figure E-2. Corn grain yield versus ET: Replication II.

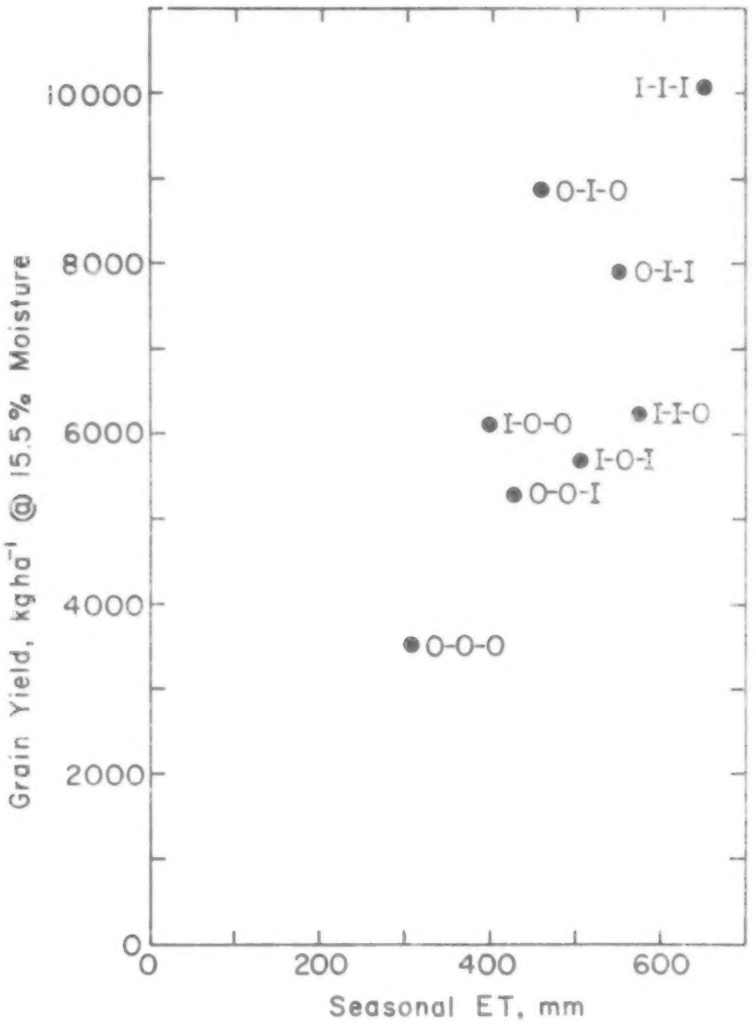

Figure E-3. Corn grain yield versus ET: Replication III.

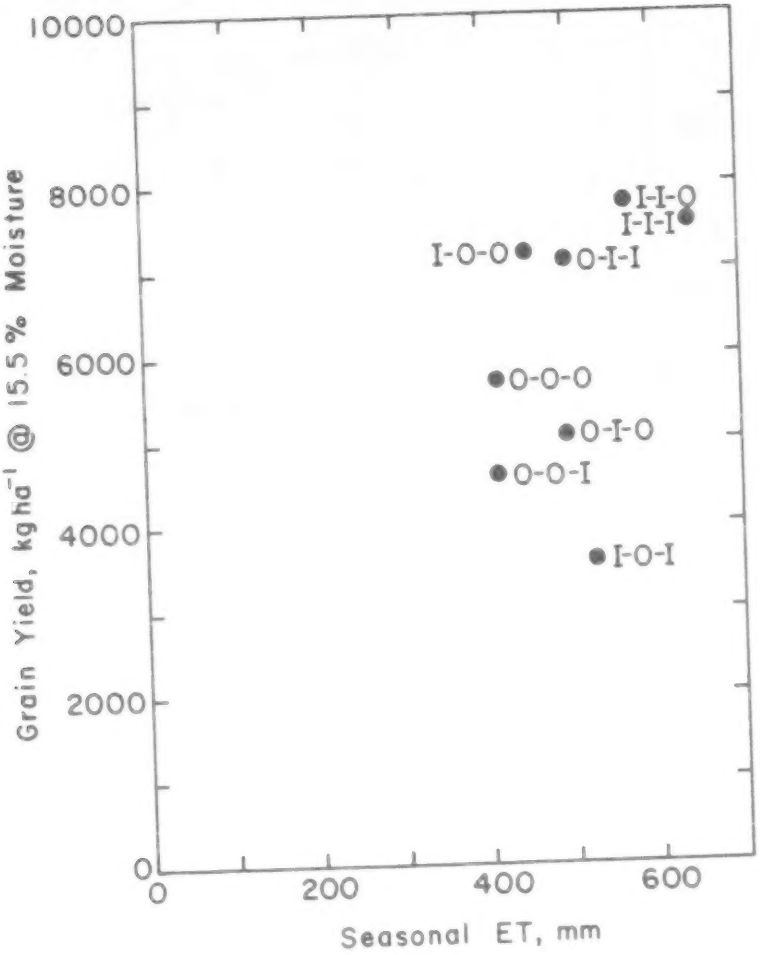

Figure E-4. Corn grain yield versus ET: Replication IV.

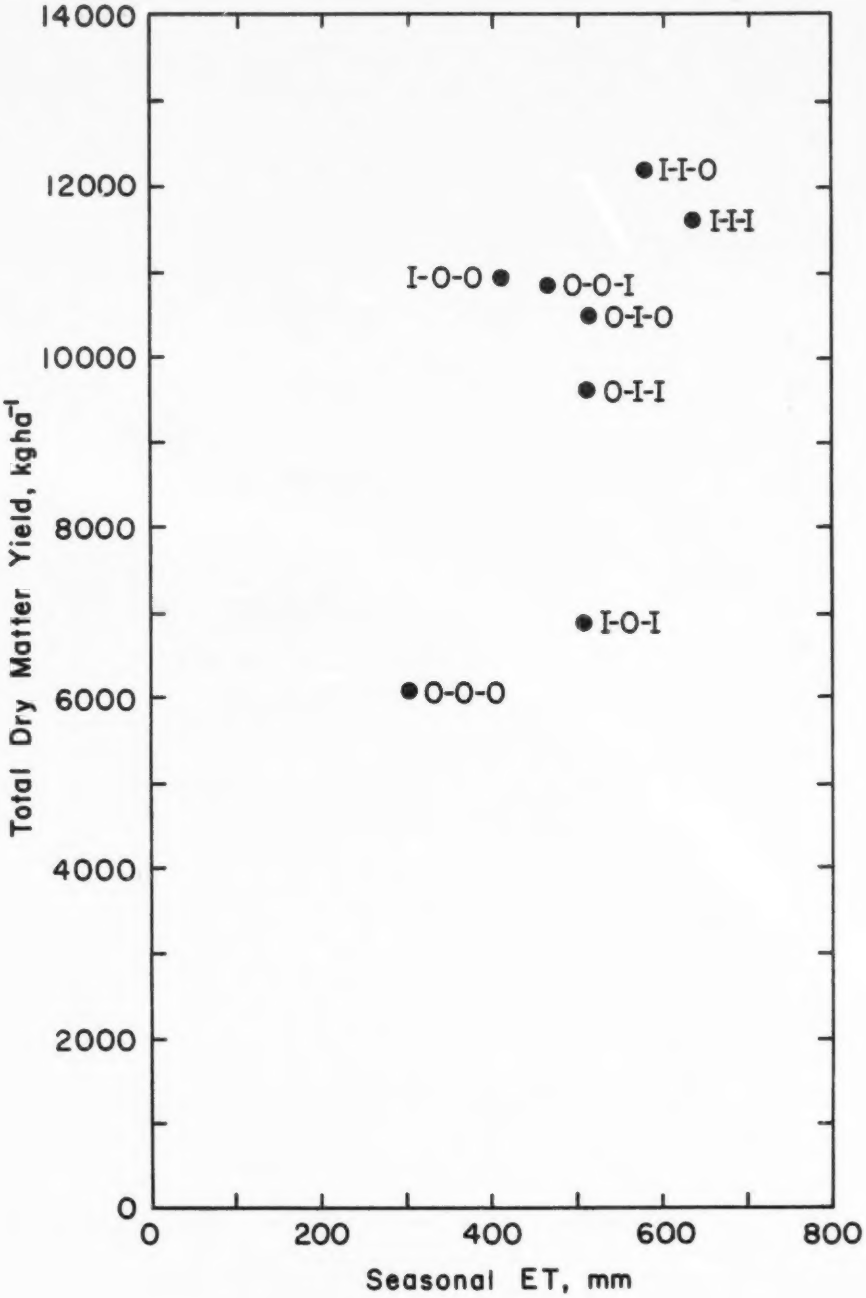

Figure E-5. Corn dry matter yield versus ET: Replication I.

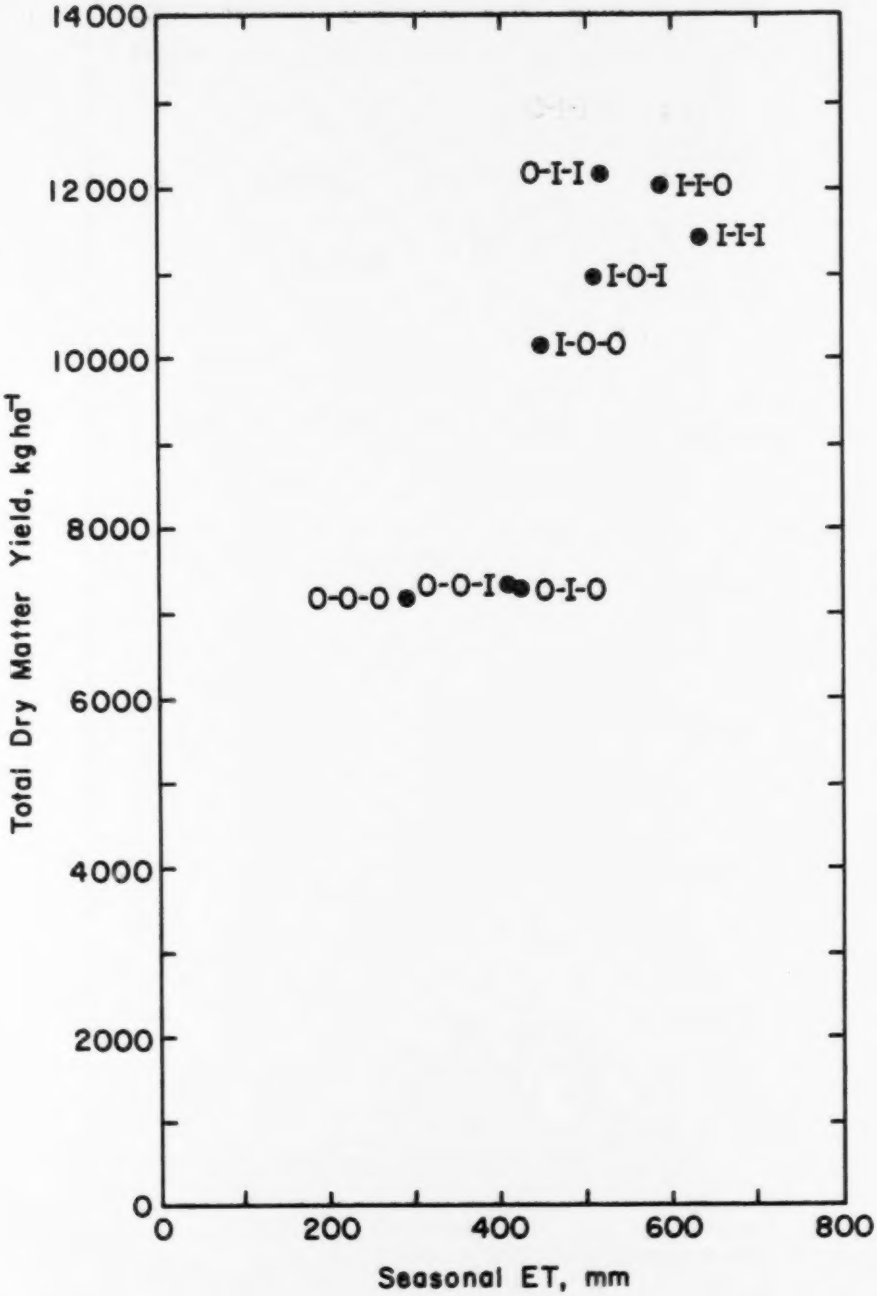

Figure E-6. Corn dry matter yield versus ET: Replication II.

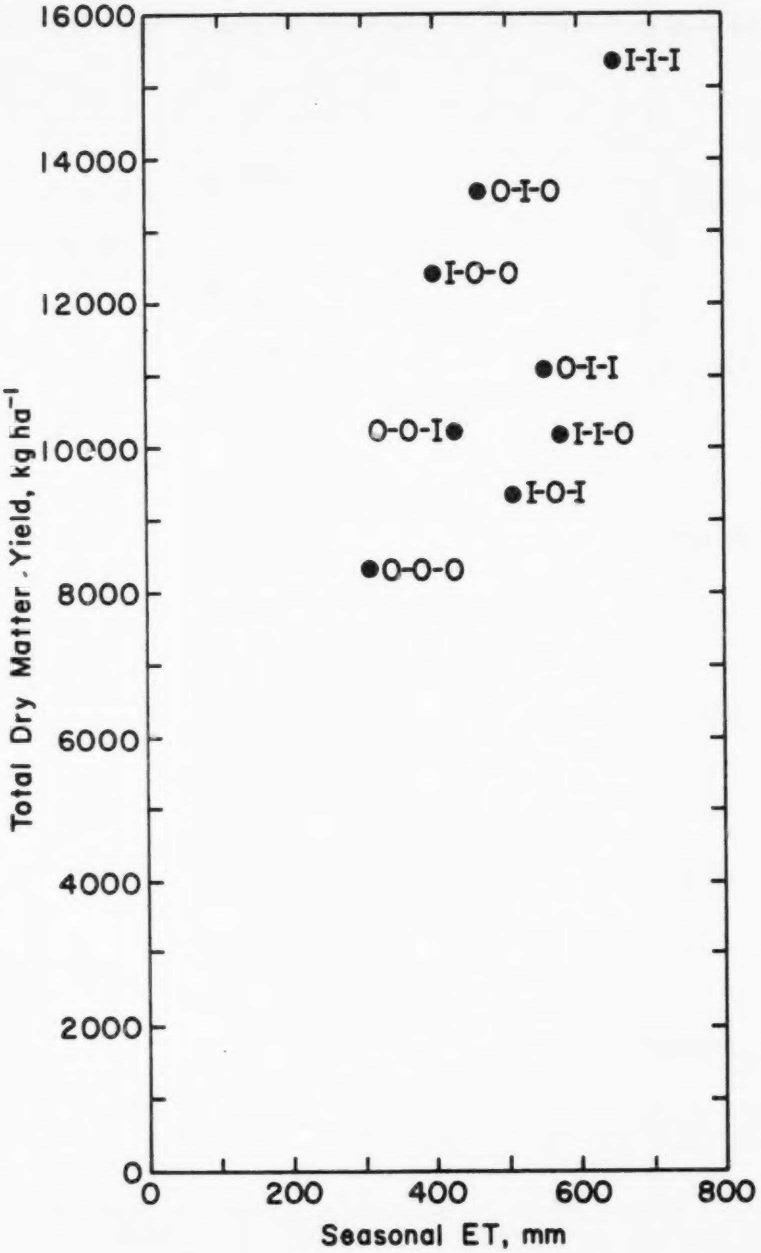

Figure E-7. Corn dry matter yield versus ET: Replication III.

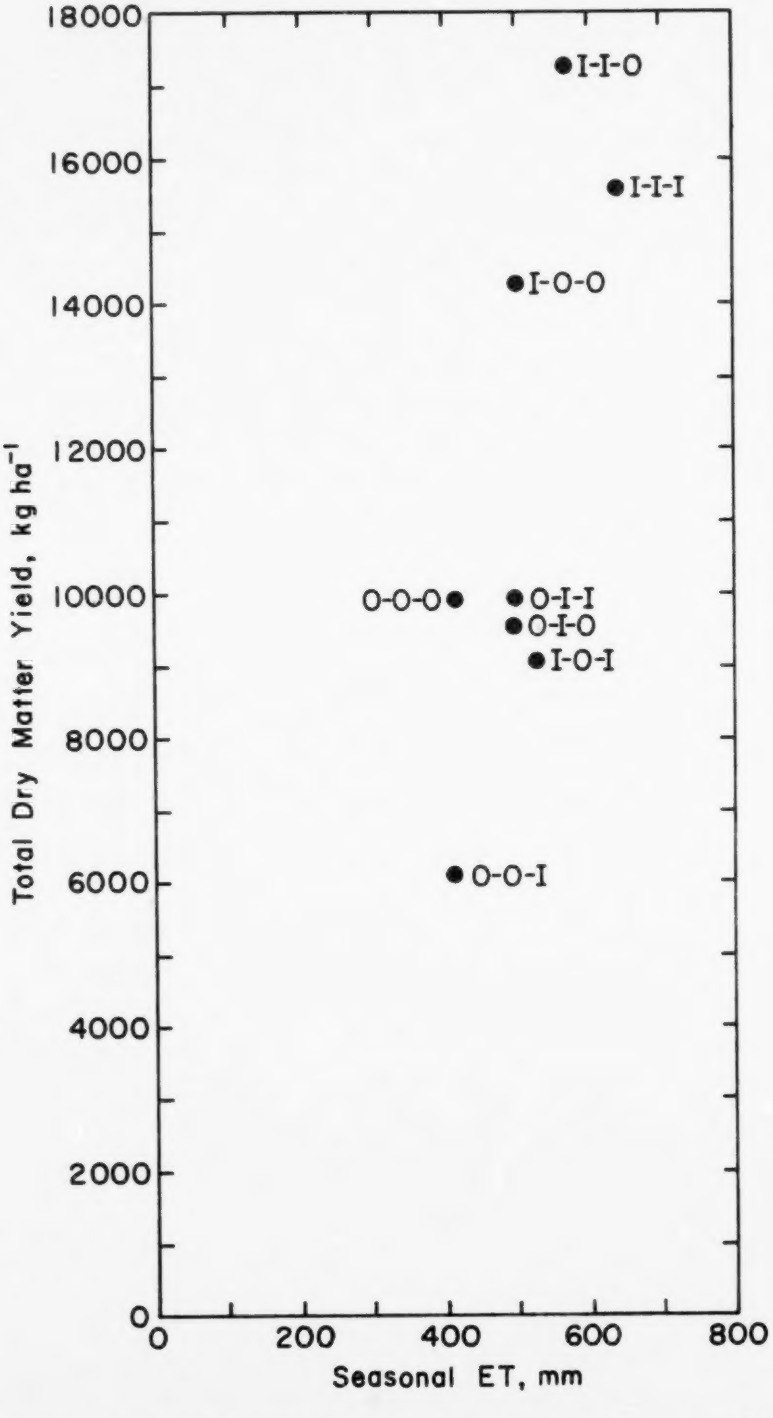

Figure E-8. Corn dry matter yield versus ET: Replication IV.

APPENDIX F

TABLE F-1. WHEAT YIELDS AND ET OF EACH PLOT

Treatment	Plot	Seasonal ET (mm)	Grain Yield (kg ha^{-1})
0-0	51	409	4388
	58	363	3848
I-0	49	479	5011
	53	467	4545
	56	493	4394
0-I	54	485	4270
	57	513	4157
I-I	50	579	4818
	52	613	4637
	55	567	4253

APPENDIX G

EFFECT OF CONTRACT RATES ON OBJECTIVE FUNCTION

Depending on the farming operation being carried out, contract rates usually consist of a minimum fixed price (to cover machinery overheads) plus a variable price based on area or yield. Typical contract costs may be expressed as follows, where the C_i's correspond to those shown in Section 10 in the text. The fixed cost portion of each cost is denoted by the superscript *. Per unit area costs are no longer applicable, so total costs will be considered. The annual fixed costs of

$$C_1 = a_1^* + a_1 A_I$$

$$C_2 = (a_2 + b_2 x) A_I$$

$$C_3 = a_3^* + a_3 A_I$$

$$C_4 = a_4^* + (a_4 + b_4 x) A_I$$

$$C_5 = a_5^* + a_5 A_I$$

$$C_6 = a_6^* + a_6 A_I$$

the irrigation system will vary with the size of the area being irrigated, although the relationship would not be linear, declining a little per unit area as the area increases. However, the relationship will be monotonic and close to linear over the range of area being considered. Energy costs depend on the volume of water pumped and are, therefore, constant. The cost of labor is fairly linearly related to the volume of water supplied and hence are also constant. Therefore,

$$C_7 = a_7^* A_I + a_7$$

$$C_8 = a_8$$

$C_9 = \$v_H^*/\text{ha}$ for y less than a given yield per unit area plus $\$v_H/\text{kg}$ for y greater than this yield

$$= a^{*}_{9}\, A_I + (a_9 + b_9 x)A_I$$

$$C_{10} = v_T y \text{ per unit area}$$

$$= (a_{10} + b_{10} x)A_I$$

The objective is, therefore, to:

$$\text{maximize } P = 0 - I$$

$$= (a + bx)A_I - (a_i - a_j A_I + b_i x A_I)$$

where $a_i = a^{\star}_{1} + a^{\star}_{3} + a^{\star}_{4} + a^{\star}_{5} + a^{\star}_{6} + a_7 + a_8$

$$a_j = a_1 + a_2 + a_3 + a_4 + a_5 + a_6 + a^{\star}_{7} + a^{\star}_{9} + a_9 + a_{10}$$

$$b_i = b_2 + b_4 + b_9 + b_{10}$$

(The terms composing a_i, a_j and b_i are able to be summed respectively as all are constants.) Therefore, the objective is to:

$$\text{maximize } P = [a + bx - (a_j + b_i x + \frac{a_i}{A_I})]A_I$$

which is the same as the objective expressed by Equation 37.

APPENDIX H

OPTIMAL DEPTH OF IRRIGATION WATER TO APPLY WITH A LINEAR PRODUCTION FUNCTION: NUMERICAL EXAMPLES

NUMERICAL EXAMPLE I:

Situation: Selected crop = wheat
Available water = 1,000,000 m^3
Available land = unlimited
Yield function: $\hat{y} = -58.3 + 0.268x$ ($r^2 = 0.933$)
(taken from Shalhevet, et al., 1976, for Jordan Rift and Bet Shean Valley, Israel).

Maximum anticipated yield, Y_{max} = 6000 kg ha^{-1} (approx. 90 bus ac^{-1}).

Corresponding maximum water consumption x_{max} = 590 mm

Gross return on crop, v_c = \$0.11 per kg (approx. \$3 per bus).

Objective:

Select the optimum land area, A_I, to be irrigated so that the function $P = (0-I)A_I$ is a maximum, where

P = net revenue

0 = output (gross revenue) per ha

I = input (costs) per ha, and

A_I = area irrigated in ha.

Method:

$$0 = v_c y$$

$$y = \hat{y}\ \frac{6000}{100}$$

$$= (-58.3 + 0.268x)\ \frac{6000}{100}$$

$$= -3498 + 16.08x$$

$\therefore 0 = (-3498 + 16.08x)\ (0.11)$

$= -385 + 1.769x\ \$\ ha^{-1}$

$I = c_1 + c_2 + c_3 + \ldots + c_{10}$, where

c_1 = cost of seedbed preparation

= \$25 per ha

c_2 = cost of seed.

A constant seeding rate of 45 kg ha^{-1} has been assumed for up to 400 mm of water consumption, then increased linearly up to 75 kg ha^{-1} for 590 mm of water consumption. If seed costs are \$0.37 per kg, then:

$c_2 = 45 \times 0.37$

= \$17 per ha for $0 \leq x \leq 400$, and

$c_2 = -6.718 + 0.0585x\ \ \$\ ha^{-1}$ for $400 \leq x \leq 590$

c_3 = cost of sowing

= \$6 per ha

c_4 = cost of fertilizing.

Colorado State University Cooperative Extension Service uses a recommendation for NO_3-N based on the soil fertility level, organic matter content and yield goal. The recommendation has a functional relationship of

$F = m + ny$

where F is the recommended NO_3-N application rate in lb N $acre^{-1}$ and y is the yield goal in bus ac^{-1}. For example, for a clay loam soil having a NO_3-N soil test level of 11 ppm and an organic matter content of 1.5 percent, the relationship would be

$F = -35 + 1.5y$ in the above units,

or $F = -39 + 0.0250y$

where F is in kg ha^{-1} and y is in kg ha^{-1}.

Now, $y = -3498 + 16.08x$

$\therefore F = -39 + 0.025\ (-3498 + 16.08x)$

$$= -126.5 + 0.402x \text{ kg ha}^{-1}$$

and with nitrogenous fertilizer costing \$0.45 per kg (actual)

$$c_4(NO_3) = -57 + 0.181x \text{ \$ ha}^{-1}.$$

Recommendations for other fertilizer elements are based solely on the soil test results and are independent of the yield goal. Therefore, assuming a phosphorus recommendation of 45 kg ha^{-1} at \$0.38 per kg

$$c_4(P_2O_5) = \$17 \text{ per ha}$$

The total cost of fertilizer is, therefore,

$c_4 = -40 + 0.181x$ \$ ha^{-1}

c_5 = cost of pesticides

= \$25 per ha

c_6 = cost of interrow cultivation

= 0

c_7 = cost of irrigation

= $c_{7L} + c_{7E} + c_{7F}$, where

c_{7L} = cost of labor

c_{7E} = variable cost of pumping (energy and maintenance)

c_{7F} = fixed cost of irrigation equipment.

The larger the area to be irrigated, the less the number of irrigations that can be accomplished with the fixed quantity of water, with a higher cost per irrigation. For a smaller area, a greater number of irrigations will be possible, each having a lower cost. Therefore, the cost of labor will be approximately the same, depending only on the quantity of water, which in this case is fixed. Assume

c_{7L} = \$1 per 1000 m^3

= \$1000 per $10^6 m^3$ ($Q = 1,000,000 \text{ m}^3$)

= \$1000/A_I per ha,

as the $10^6 m^3$ are to be applied to an area, A_I.

Assume c_7E = \$3.00 per 1000 m^3

= \$3000/A_I per ha

c_{7F} = \$25 per ha

This cost will decrease with increasing area, but only by a small amount within the range of areas considered.

$\therefore\ c_7 = 25 + 4000/A_I$ \$ ha^{-1}

c_8 = cost of water.

Consider the charges for water to be on an escalating rate of

c_8 = \$1 per 1000 m^3 for $0 < q \leq 250{,}000\ m^3$

= \$2 per 1000 m^3 for $250{,}000 < q \leq 500{,}000\ m^3$

= \$3 per 1000 m^3 for $500{,}000 < q \leq 750{,}000\ m^3$

= \$4 per 1000 m^3 for $750{,}000 < q \leq 1{,}000{,}000\ m^3$

where $q \leq Q$

As $Q = 1{,}000{,}000\ m^3$

c_8 = \$2500

= \$2500/A_I per ha

c_9 = cost of harvesting

= \$25 per ha up to 1500 kg ha^{-1} plus

\$0.002 per kg for greater than 1500 kg ha^{-1}

When $y = 1500$ kg ha^{-1}, $x = 311$ and c_9 = \$25 per ha

When $y = 6000$ kg ha^{-1}, $x = 590$ and c_9 = \$34 per ha

$\therefore\ c_9$ = \$25 per ha for $0 \leq x \leq 311$

and $c_9 = 15 + 0.0323x$ \$ ha^{-1} for $311 \leq x \leq 590$

c_{10} = cost of disposing

= \$0.004 per kg in own bin + \$0.0002 (kg km^{-1}) for hauling.

Assuming a 10 km haul

$$c_{10} = \$(0.004 + 0.002) \text{ per kg}$$

$$= \$0.006 \text{ per kg}$$

$$= -21 + 0.0965x \ \$ \ \text{ha}^{-1}$$

Therefore, the objective function is to

$$\text{maximize } P = [0 - \sum_{i=1}^{10} c_i]A_I$$

$$= [-385 + 1.769x - (20 + 0.2775x + c_2 + \frac{6500}{A} + c_9)]A_I$$

$$A_I = \frac{Q}{x}$$

$$= \frac{1{,}000{,}000 \text{ m}^3}{x \text{ mm}}$$

$$= \frac{10^5}{x} \text{ ha where x is in mm}$$

$$\therefore \text{ Maximize } P = -405 \left(\frac{10^5}{x}\right) + (1.4265)(10^5) + (c_2+c_9)\frac{10^5}{x}$$

For $0 < x \leq 311$,

$$P = -405 \left(\frac{10^5}{x}\right) + (1.4265)(10^5) + 42 \left(\frac{10^5}{x}\right)$$

$$= -365 \left(\frac{10^5}{x}\right) + (1.4265)(10^5)$$

and P is a maximum when x is a maximum.

When $x = 341$

$$P = \$35{,}612$$

For $311 < x \leq 400$,

$$P = -405\left(\frac{10^5}{x}\right) + (1.4265)(10^5) + 32\left(\frac{10^5}{x}\right) + (0.0323)(10^5)$$

and P is a maximum when x is a maximum

When $x = 400$

$$P = \$52{,}630$$

For $400 < x \leq 590$

$$P = -405\left(\frac{10^5}{x}\right)+(1.4265)(10^5) + 8.282\left(\frac{10^5}{x}\right)+(0.0908)(10^5)$$

and again P is a maximum when x is a maximum

When $x = 590$

$$P = \$84,490$$

Therefore, the maximum profit is obtained when the amount of water consumed is a maximum, up to the limit of

$x = x_{max}$.

Therefore, the optimum area is the smallest over which the fixed water quantity can be applied so that x does not exceed x_{max}.

$$\text{i.e., } A_{opt} = \frac{Q}{x_{max}}$$

$$= \frac{1,000,000 \text{ m}^3}{590 \text{ mm}}$$

$$= 169.5 \text{ ha}$$

Most of the cost factors are either independent of the area irrigated (c_8) or increase with area (c_1, c_3, c_5, c_6, c_7). These can be eliminated from any sensitivity analysis. The remainder (c_2, c_4, c_9, and c_{10}) all affect net profit in proportion to the yield obtained from the total area. They can only be decreased by decreasing the total yield. Decreasing the total yield will obviously decrease gross profits by a greater amount (otherwise the most profitable practice would be to grow zero wheat!). Therefore, it may be seen qualitatively that the most profitable practice is to irrigate that area, A_I, of crop which will consume that depth of water, x_{max}, giving the peak yield, Y_{max}.

The cost factors in the profit calculation above take into account only those variable and fixed costs associated directly with the irrigation enterprise. From the point of view of the farm budget, other fixed costs, such as land taxes, loan interest and overheads, would have to be subtracted in addition to a contingency sum for the inevitable unforeseen costs. These factors do not affect the optimal irrigation policy as derived.

NUMERICAL EXAMPLE II:

Situation:

Selected crop: wheat
Available water: unlimited
Available land: 200 ha

Yield function, crop value and costs the same as in Numerical Example I.

Objective:

Select the optimum quantity of water to make available for crop consumption so that the function

$$p = P/A_I = 0-I$$

is a maximum, where p is the net profit per unit area and the other terms are as defined in the previous example.

c_1 through c_6 will be the same as before

c_7 will depend on the depth of water applied:

1 mm over 1 ha = 10 m^3

$x = \frac{q}{10}$ mm where q is the volume of water applied per unit area, in $m^3\ ha^{-1}$

$$c_7 = \$25 \text{ per ha} + \$4.00 \text{ per } 1000\ m^3$$

$$= \$25 \text{ per ha} + \$\frac{4}{1000}q$$

$$q = 10\ x$$

$$\therefore\ c_7 = 25 + 0.04x\ \$\ ha^{-1}$$

c_8 can be expressed in terms of x. At \$1 per 1000 m^3, the cost per ha is \$1q/1000 where q is the volume of water applied per ha. As q = 102x, then

$$c_8 = \$0.01\ x \text{ per ha for } 0 < x \le 125$$

$$= \$0.02\ x \text{ per ha for } 125 < x \le 250$$

$$= \$0.03\ x \text{ per ha for } 250 < x \le 375$$

$$= \$0.04\ x \text{ per ha for } 375 < x \le 500$$

and say c_8 = \$0.10 x per ha for x > 500
where the limits of q in the previous example have been converted to limits of x by recognizing that as

$$x = \frac{q}{10}$$

and $q = \frac{Q}{200}$

then $x = \frac{Q}{2000}$.

c_9 and c_{10} are as before.

The objective, therefore, is to

$$\text{maximize } p = -385 + 1.769x - (20 + 0.3175x + c_2 + c_8 + c_9)$$
$$= -405 + 1.4515x - (c_2 + c_8 + c_9)$$

where c_2, c_8, and c_9 vary with x over different ranges of x. Observation of the coefficients of x in these cost factors will show that they are much smaller than the coefficient of x in the expression for p, and hence, again, maximum profit is associated with maximum $x (x = x_{max})$. If the coefficients of x in the cost factors are increased substantially, the effect will be to make the coefficient of x negative in the expression for p. In this case, irrigating will not be feasible.

The remaining possibility is to increase the cost of water, where the charge is on an escalating scale. (If the charge were constant and substantially increased, the effect would simply be to reduce profitability.) If, for example, water charges were increased tenfold for up to 500 mm, so that

$$
\begin{aligned}
c_8 &= \$0.1\ x \text{ per ha for } 0 \le x \le 125\\
&= \$0.2\ x \text{ per ha for } 125 < x \le 250\\
&= \$0.3\ x \text{ per ha for } 250 < x \le 375\\
&= \$0.4\ x \text{ per ha for } 375 < x \le 500
\end{aligned}
$$

and $c_8 = \$2.0\ x$ per ha for $x > 500$

then:

when x =	200	300	400	500	590	499	501	mm
p =	-184.2	-64.1	45.7	142.1	87.5	141.1	141.5	$ ha^{-1}

In this case, maximum profit is attained when x=500 mm, i.e., the additional yield obtained by the crop consuming additional water does not justify the additional water. The breakpoint comes where the incremental charge for water jumps from $40 per 1000 m^3 to $200 per 1000 m^3.

Therefore, unless the charge for water is on an escalating scale per volume, with the maximum charge very high in relation to the value of the crop, the most profitable practice will be to provide the crop with the depth of water corresponding to maximum yield.